Assessment of Nutrient Status and Trends in the Delta in 2001–2016:

Effects of drought on ambient concentrations and trends

March 2018

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Acronyms and Abbreviations

ASC	Aquatic Science Center
C3, D6, etc.	Water quality monitoring stations in the Delta; see Figure 1
CAWSC	California Water Science Center
DIN	Dissolved inorganic nitrogen
DO	Dissolved oxygen
DWR	Department of Water Resources
EMP	Environmental Monitoring Program
FAV	Floating aquatic vegetation
HF	High-frequency
IEP	Interagency Ecological Program
MWQI	Municipal Water Quality Investigations (branch of the California Department of Water Resources)
NMF	Non-negative matrix factor
O&M	Operation and maintenance
OLU	Operational landscape units
RMP	Regional Monitoring Program
SAV	Submerged aquatic vegetation
SFEI	San Francisco Estuary Institute
SJR	San Joaquin River
SKT	Seasonal Kendall Test
SPLP	Sources, Pathways, Loadings, and Processes
ST	Status and Trends
TMDL	Total Maximum Daily Load
TN	Total nitrogen
TP	Total phosphorus
USGS	U.S. Geological Survey
WWTF, WWTP	Wastewater treatment facility/plant
WY	Water year

Executive Summary

Nutrients and the effects of nutrients on water quality in the Sacramento-San Joaquin Delta is a priority focus area for the Delta Regional Monitoring Program (Delta RMP). The Program's first assessment question regarding nutrients is: "How do concentrations of nutrients (and nutrient-associated parameters) vary spatially and temporally?" In this report, we used data collected by the Department of Water Resources Environmental Monitoring Program (DWR-EMP) to answer this question. This report builds on previous data synthesis reports by adding the latest data from the recent drought years, water years (WY) 2012-2016.

Looking at the most recent 16 years (WY 2001–2016), the analysis confirmed previously reported declining trends in the San Joaquin River for nutrient concentrations at Vernalis and chlorophyll-a concentrations at Buckley Cove and Disappointment Slough. A slight increasing trend for dissolved oxygen at Buckley Cove was also detected which could be confirmation that management actions for the San Joaquin River Dissolved Control Program are having the desired effect. Finally, at stations in Suisun Bay, the Confluence region, and Franks Tract, chlorophyll-a showed modest increasing trends, which were not evident in previous analyses. The baseline chlorophyll-a concentrations at these stations were already low so the absolute increases in biomass are quite small.

The data from the 16 years were grouped into categories of "dry years" or "wet years" for an additional test to evaluate differences between these types of years. The analysis revealed that the spring and summer concentrations for both nitrogen and phosphorus species were 30% to 40% higher on average during dry years compared to wet years. Another finding was that chlorophyll-a concentrations in Suisun Bay were higher during wet years.

During recent drought years (WY 2012–2016), in areas of the Delta where Sacramento River water dominates, ammonium had higher peak concentrations and stronger seasonality. Phosphorus concentrations had apparent (but not statistically significant) increasing trends. Also, during WY2015 and WY2016, there were large algae blooms (dominated by centric diatoms by biovolume in WY2016) in the Central Delta.

In areas of the Delta that are dominated by San Joaquin River water, phosphorus concentrations at Buckley Cove were much higher overall during the drought compared to the WY 2006-2011 period. Also, summer chlorophyll-a concentrations in the San Joaquin River at Vernalis neared or exceeded 100 μg/L, indicative of large algal blooms (dominated by centric diatoms by biovolume in WY2016). Blooms of this magnitude or larger have occurred at this station before the drought. However, across the entire 16-year period, summer chlorophyll-a concentrations at Vernalis appear to be highest during critical or dry water years (2001–02, 2004, 2007–09, 2012–16).

The new analyses presented in this report and the findings from earlier reports constitute encouraging early progress toward answering the Delta RMP's assessment questions. Specifically, due to the existence of long-term data sets and synthesis efforts, spatial and temporal trends in the concentrations of nutrients and nutrient-related parameters are reasonably well understood and so are the magnitudes of the most important sources of nutrients from outside the Delta. However, additional synthesis work could be done to understand the factors behind these trends. Obvious factors behind the observed trends have been explained, but a detailed analysis to determine what was causing all the trends was beyond the scope of this report and should be considered for future work.

In this report, we also summarize what is known regarding each of the Delta RMP's assessment questions based on recent work. A major gap in our knowledge is how the Delta ecosystem is influenced by nutrients. Answering this question will require establishing linkages between nutrients and primary productivity, macrophytes, harmful algal blooms, and dissolved oxygen, taking other factors and confounding variables into account. Ramping up to answer these questions will take significant effort and careful planning. The Delta Nutrient Research Plan, being led by the Central Valley Regional Water Quality Control Board, will provide the roadmap for establishing these linkages.

Finally, large knowledge gaps remain about nutrient sinks, sources, and processes within the Delta. The mechanistic, water quality-hydrodynamic models being developed for the Delta may be able to address these questions in the future. However, the important processes, time-scales, and spatial scales need to be better defined in order to know the best way forward.

Regardless of the specific tools, addressing the complex issue of nutrients in Delta will require an adaptive management framework that includes status and trends monitoring, modeling, and targeted laboratory and field experiments designed to test the effects of management actions, and to elucidate model mechanisms and parameterization.

1 Introduction

There is growing concern that the Delta may be experiencing adverse impacts from nutrients and that these impacts may be increasing, concurrent with changes in other factors such as light, grazing, flow, salinity, stratification, and temperature (Dahm et al. 2016). Observed impacts that may be linked to nutrients include the following (also see the conceptual diagram in **Figure 2**):

1. *Changes in phytoplankton biomass and composition.* Hypothesized contributing factors include elevated ammonium levels, changes in the ratio of nitrogen to phosphorus (Dugdale et al. 2007, Glibert 2012, Parker et al. 2012), and the effects of invasive clams (Kimmerer 2002 and 2006, Thompson et al. 2008, Bennett 2005).
2. *Harmful cyanobacterial blooms.* Cyanobacterial harmful algal blooms (cyanoHABs) have occurred periodically in the Delta since 1999 (Lehman et al. 2005) and potentially signal changes in ecosystem response. Hypothesized contributing factors include elevated water temperatures, longer water residence times, and high nutrient levels, particularly ammonium.
3. *Submerged and floating aquatic macrophytes.* Non-native species of submerged aquatic vegetation (SAV) and floating aquatic vegetation (FAV) have become abundant and widespread in the Delta. The efficacy of nutrient management to control the abundance and distribution of nuisance macrophyte species is being investigated.
4. *Periodic low dissolved oxygen (DO) in back sloughs.* Nine waterways within the Delta are listed by the state as impaired because of periodic low DO events (SWRCB 2012). Most of the back slough type habitat on the south and east side of the Delta is impaired due to low DO. Primary causes of the low DO events are not known, but nutrients from localized agricultural and urban runoff and upstream sources are hypothesized as contributing factors, along with elevated temperature, poor circulation, and long water residence times.
5. *Drinking water impacts.* Several conveyance facilities and reservoirs used for storage of source water pumped from the Delta are plagued by episodic taste and odor problems and clogging issues due to nuisance algal blooms. Whether nutrient and nutrient-associated constituents conveyed from the Delta are contributing significantly to this excessive algal growth (and whether controls on nutrient sources to affect nutrient levels in the Delta would be a cost-effective control option) is uncertain. Additional monitoring and specific studies are needed to directly address this question.

The Central Valley Regional Water Quality Control Board and a Stakeholder and Technical Advisory Group are developing a *Delta Nutrient Research Plan* to determine whether and how ecosystem conditions in the Delta can be improved by managing nutrients. Many of the Delta RMP's assessment questions are directly relevant to the *Nutrient Research Plan* (**Table 1**). The Delta RMP is seeking to answer these questions as much as possible by synthesizing data and information generated by other monitoring agencies and researchers.

This report focuses on the Delta RMP's "Status and Trends" (ST) questions related to concentrations of nutrients and nutrient-related parameters (see question ST1 and sub-questions in the right-hand column in **Table 1**). The specific objectives for this report are:

1. Extend data analysis and observations from these previous reports to include new data (2012–2016) and additional nutrient-related parameters (chlorophyll-a, a measure of overall phytoplankton abundance, and dissolved oxygen)
2. Summarize results from the following, recently completed projects:
    a. Aquatic Science Center (ASC) project funded by DWR, synthesizing DWR-EMP data (2000–2011); *Characterizing and quantifying nutrient sources, sinks and transformations in the Delta: Synthesis, modeling, and recommendations for monitoring* (Novick et al. 2015).
    b. ASC project funded by the Delta Science Program analyzing IEP-EMP data (1975–2011) with a focus on spatial variability, potential subregions for nutrient modeling, and assessment, and limited characterization of long-term trends: *Summary and evaluation of Delta subregions for nutrient monitoring and assessment* (Jabusch et al. 2016).
    c. U.S. Geological Survey (USGS) report funded by the Delta RMP, synthesizing high-frequency sensor data: *Planning and operating a high frequency nutrient and biogeochemistry monitoring network: the Sacramento-San Joaquin Delta* (Kraus et al., 2017; Downing et al., 2017; Bergamaschi et al., 2017).
3. This report concludes with a brief summary of the state-of-knowledge about each of the Delta RMP's assessment questions based on the new analyses presented here and other recent reports.

Table 1. Delta RMP assessment questions for nutrients.

Italicized bold-faced questions are assessment questions that were prioritized by program participants for the initial program.

Type	Core Management Questions	Nutrient Assessment Questions
Status & Trends	***Is there a problem or are there signs of a problem?*** a. Is water quality currently, or trending towards, adversely affecting beneficial uses of the Delta? b. Which constituents may be impairing beneficial uses in subregions of the Delta? c. Are trends similar or different across different subregions of the Delta?	ST1. How do concentrations of nutrients (and nutrient-associated parameters) vary spatially and temporally? A. Are trends similar or different across subregions of the Delta? B. How are ambient levels and trends affected by variability in climate, hydrology, and ecology? ***C. Are there important data gaps associated with particular water bodies within the Delta subregions?*** ***ST2. What is the current status of the Delta ecosystem as influenced by nutrients?*** A. ***What is the current ecosystem status of habitat types in different types of Delta waterways, and how are the conditions related to nutrients?***
Sources, Pathways, Loadings & Processes	Which sources and processes are most important to understand and quantify? a. Which sources, pathways, loadings, and processes (e.g., transformations, bioaccumulation) contribute most to identified problems? b. What is the magnitude of each source and/or pathway (e.g., municipal wastewater, atmospheric deposition)? c. What are the magnitudes of internal sources and/or pathways (e.g. benthic flux) and sinks in the Delta?	***SPLP1. Which sources, pathways, and processes contribute most to observed levels of nutrients?*** *A. How have nutrient or nutrient-related source controls and water management actions changed ambient levels of nutrients and nutrient-associated parameters?* *B. What are the loads from tributaries to the Delta?* *C. What are the sources and loads of nutrients within the Delta?* *D.* ***What role do internal sources play in influencing observed nutrient levels?*** *E. Which factors in the Delta influence the effects of nutrients?* *F.* ***What are the types and sources of nutrient sinks within the Delta?*** *G. What are the types and magnitudes of nutrient exports from the Delta to Suisun Bay and water intakes for the State and Federal Water Projects?*
Forecasting Scenarios	a. How do ambient water quality conditions respond to different management scenarios? b. What constituent loads can the Delta assimilate without impairment of beneficial uses? c. What is the likelihood that the Delta will be water quality-impaired in the future?	FS1. How will ambient water quality conditions respond to potential or planned future source control actions, restoration projects, and water resource management changes?

2 Summary of New Analyses

2.1 Approach

The analysis presented here focuses on the spatial, seasonal, and temporal variability of nutrients in the Sacramento-San Joaquin River Delta. This analysis expands upon and updates analyses described in two recent reports:

1. *Characterizing and quantifying nutrient sources, sinks and transformations in the Delta: synthesis, modeling, and recommendations for monitoring* (Novick et al. 2015).
2. *Analysis of spatial, seasonal, and temporal variability, and long-term trends in nutrient concentrations in the Sacramento-San Joaquin Delta and Suisun Bay during the period 1975–2013.* Appendix 2 in *Summary and Evaluation of Delta Subregions for Nutrient Monitoring and Assessment* (Jabusch et al. 2016).

The same methods for trend analysis were used in this report as these two previous reports.

Dataset: The data used for this analysis were collected by the Department of Water Resources Environmental Monitoring Program (DWR-EMP), which is part of the Interagency Ecological Program. The DWR-EMP conducts discrete (grab sample) physical-chemical monitoring (near-monthly) of macronutrients (inorganic forms of nitrogen, phosphorus, and silicon); total suspended solids; total dissolved solids; total, particulate and dissolved organic nitrogen and carbon; chlorophyll a, dissolved oxygen, specific conductance, turbidity, Secchi depth, and water temperature. Stations included in this analysis are shown below. Duplicate results for the same station-date-depth were averaged prior to generating graphics or performing statistical analyses. For more information about the monitoring program see the program website: http://www.water.ca.gov/iep/activities/emp.cfm.

Station Code	**Location**	**Subregion**
C3	Sacramento River @ Hood	Sacramento River
D26	San Joaquin River at Potato Point	North Central Delta
MD10	Disappointment Slough @ Bishop Cut	North Central Delta
P8	San Joaquin River @ Buckley Cove	North Central Delta
D19	Frank's Tract	South Central Delta
D28A	Old River @ Rancho Del Rio	South Central Delta
C10	San Joaquin River near Vernalis	South Delta
D4	Sacramento River above Point Sacramento	Confluence
D6	Martinez	Suisun Bay
D7	Grizzly Bay	Suisun Bay
D8	Suisun Bay off Middle Point near. Nichols	Suisun Bay

Statistical Methods for Trends Analysis: The Seasonal Kendall test (SKT, Helsel and Hirsch 2002, Hirsch et al. 1982) test was used to test for trends in the data. It is a non-parametric rank test that has been proven robust in evaluating trends in time series that have strong seasonality. The SKT is an extension of Mann-Kendall test, but it does not make assumptions about the distribution of the data and allows missing values and censored data without biasing the analysis. More specifically, the SKT accounts for seasonality by computing the Mann-Kendall test on each month separately, and then combining the results. As described by Jassby (2008), long-term trends were estimated after adjusting for total river inflow using locally weighted regression with a span of 0.5 and a locally linear fit.

For this report, we built upon the previous work by analyzing the most recent available monitoring data from DWR-EMP through the end of Water Year (WY) 2016. We also expanded the analysis to include additional parameters (orthophosphate, PO_4, total phosphorus, TP, dissolved oxygen, DO, and chlorophyll-a, Chl-a) that were not included or in Novick et al. (2015) or were only discussed briefly. Our analysis focuses on a 16-year period spanning from water years (WY) 2001 to 2016 (October 1, 2001 to September 30, 2016). The updated and additional analyses include:

1. *Updated time series plots of water quality data:* Updated and additional time series data allow for visualization of water quality data and for trends or other changes.
2. *Updated trend analyses:* Statistical analyses for trend in inflow-adjusted data for each station, using the Seasonal Kendall Test.
3. *Updated plots of nutrient concentrations by season:* Updated and additional box plots of concentrations and ratios by station and by month to evaluate seasonal and spatial variability; a comparison of drought year data with those of wet and normal years.
4. *Water Year 2016 nutrient concentrations compared to previous observations*: A comparison of the results from the most recent year of data (WY2016) with the range in concentrations across the entire time period.

For additional detail on the statistical methods and analytical approaches, see Novick et al. (2015) and Jabusch et al. (2016).

2.2 Results and Discussion

This section presents the key findings from the updated analyses, with an emphasis on trends. All figures are presented in a separate section of the report (see *Figures*, beginning on page 54). Figure 1 shows the location of water quality monitoring stations (C3, D6, P8, MD10, etc.) referred to in the text, tables, and figures below.

Updated Time Series Plots of Water Quality Data

The following paragraphs highlight notable changes in the time series that occurred in the recent drought years (WY 2012–16), as compared to previous years (WY 2001–2011). **Figures 4–27** show monthly time series for nitrogen forms (ammonia [NH_4], nitrate [NO_3], dissolved nitrogen [DIN], and total nitrogen [TN]), phosphorus forms (dissolved orthophosphate [PO_4] and total phosphorus [TP]), chlorophyll-a (Chl-a), and dissolved oxygen (DO), for a 16-year period extending from water year 2001 to water year 2016. The newer data for WY 2012–2016 are plotted in red on these graphs.

Sacramento River Dominated Stations

In areas of the Delta that are dominated or strongly influenced by Sacramento River water, peak ammonium and dissolved orthophosphate concentrations during the recent drought years hit the highest levels for the 16-year dataset. Also, during 2015 and 2016, there were unusually large algae blooms in the Central Delta. Specific observations are highlighted below:

- *Ammonium had higher peak concentrations and stronger seasonality at some stations.* The drought year data include the highest peak ammonium concentrations at station C3 below the Sacramento Regional Wastewater Treatment Plan for the entire 16-year period (**Figure 4**, upper panel). Also, at several Central Delta stations (D19, D26, and D28, **Figure 5**), winter ammonia concentrations were noticeably higher in the drought years than during WY 2010 and WY 2011, which were wetter. Summer concentrations at the Central Delta stations do not appear different from those observed prior to 2012, and therefore the seasonal variation in concentrations was more pronounced during the drought. The pattern suggests lower than average flows in the winter and, therefore, less dilution of presumed constant ammonium inputs[1], contributing to higher than average peak concentrations in the Sacramento River during the winter. The large seasonal swings of ammonium at Central Delta

[1] Average loads from the dominant ammonium source to the Sacramento River did not change during the drought. The five-year average load of ammonium from the Sacramento Regional Wastewater Treatment Plant (SRWTP) for WY 2007-2011 was approximately 13,400 kg N/d. The five-year average load of ammonium from SRWTP for WY 2012-2016 was approximately 13,500 kg N/d.

stations indicate that it gets consumed as it passes along the flow path due to biological uptake and/or transformation, especially during summer months.

- *Dissolved orthophosphate and total phosphorus concentrations increased during the drought.* Concentrations of dissolved orthophosphate and total phosphorus increased at all stations that are dominated or strongly influenced by Sacramento River water (**Figures 16**, **17**, **19, and 20**). A plausible hypothesis to explain this phenomenon is that there is a relatively constant load of phosphorus from wastewater plants discharging to the river. Lower river flows mean less dilution and higher phosphorus concentrations. However, there are other sources of phosphorus and a range of factors that affect its fate and transport, so additional research would be required to confirm this hypothesis.
- *Large algal blooms were observed, especially at Central Delta stations.* Concentrations of chlorophyll-a at stations D26 and D19 exceeded 60 µg/L in the summer of 2016 (**Figure 23**). Phytoplankton taxonomy data from the DWR Environmental Monitoring Program indicate that the bloom in WY 2016 was dominated by centric diatoms by biovolume. These chlorophyll-a maxima coincide with reductions in nitrate, dissolved inorganic nitrogen, and total nitrogen, but not dissolved orthophosphate (**Figures 8, 11, 14, and Figure 17**). The bloom may have extended to station MD10 in the eastern North Central Delta (**Figure 24**) and station D4 in the Confluence (**Figure 23**). This bloom or a similar one was captured by the high-frequency sensors deployed at Rio Vista and Prisoner Point by USGS and DWR, respectively A short trace of the data is shown in Novick et al. (2016, Figure 4.7).

San Joaquin Dominated Stations

In areas of the Delta that are dominated by San Joaquin River water, phosphorus concentrations appeared to increase during the drought, especially at Buckley Cove. Algae blooms occurred at Vernalis during the drought years, which was consistent with the pattern of blooms during dry years. Specific observations are highlighted below:

- *Elevated concentrations of dissolved orthophosphate and total phosphorus were observed in the San Joaquin River at Buckley Cove.* Phosphorus concentrations at Buckley Cove (P8) were much higher overall during the drought compared to the WY 2006-2011 period (**Figure 21**). The peak concentrations in WY 2012-2016 returned to levels not seen since WY 2001-2004. Reduced dilution during the drought does not explain the recent high concentrations because the inflows to the Delta in WY 2007-2009 were similar to the recent drought years (**Figure 40**). The concentrations at Buckley Cove were higher than at the Vernalis station located upstream on the San Joaquin River (**Figures 18 and 21**).

- *The highest peak concentrations of dissolved orthophosphate at Vernalis occurred during winter in 2015 and 2016 which were both during the drought.* The peak winter concentrations in WY2015 and WY2016 exceed 0.3 mg/L and are the highest in the entire 16-year period. Plotting the dissolved orthophosphate concentrations versus San Joaquin River flow shows that the concentrations were actually highest during the periods of higher flow (Figure 28). Therefore, the peak concentrations in the winter likely indicate periods of runoff during winter storms.
- *Large algal blooms in the San Joaquin River at Vernalis.* Chlorophyll-a concentrations in the San Joaquin River neared or exceeded 100 μg/L in the summers of 2012, 2013, 2015, and 2016, suggesting large algal blooms in these years (**Figure 24**). Phytoplankton taxonomy data from the DWR Environmental Monitoring Program indicate that the bloom in WY 2016 was dominated by centric diatoms by biovolume. Blooms of this magnitude or larger have occurred at this station before the drought. However, across the entire 16-year period, summer chlorophyll-a concentrations at Vernalis appear to be highest during critical or dry water years (2001–02, 2004, 2007–09, 2012–16).

Updated Trend Analyses

The most recent 16-year dataset was analyzed for temporal trends at individual stations. The statistical method used was a Seasonal Kendall Test on flow adjusted data following the procedures used in Jabusch et al. (2016). To calculate flow-adjusted concentrations, the relationship between the observed concentrations at a site and inflow to the Delta is used to correct for variance in the concentrations that would be expected purely from changes in the flow (see **Figure 29** for an illustration). For the first analysis, the full dataset for WY 2001–2016 was used. A second analysis was run on just the most recent 5 years during the drought (WY 2012–2016).

Trends for the Most Recent 16-year Period (WY2001–2016)

The trend analysis detected several significant trends in the 16-year period extending from WY 2001 to 2016 (**Figures 30 and 31**).

Nitrogen and Phosphorus (Figures 30 and 31)

- *Significant decreases in nitrogen and phosphorus in the San Joaquin River at Vernalis (C10).* Decreasing trends (3% to 5% per year) were detected in concentrations of nitrate, dissolved inorganic nitrogen, and total nitrogen but not in ammonium.

Decreasing trends were also detected in dissolved orthophosphate and total phosphorus (around 3% per year). These trends could be due to many factors such as reduced runoff (and hence non-point source loads) during the drought and non-point source controls, such as the reduction of discharges from the Grassland Bypass Project (Grassland Bypass Project Oversight Committee 2013), although more evidence is needed to confirm this.

- *A significant decrease in ammonium was detected in the San Joaquin River at Buckley Cove (P8).* This station is downstream of the Stockton WWTP. The decrease in ammonium at this station is expected, as the major source of ammonium to this stretch of river came from the Stockton WWTP, which added biological nutrient removal (or tertiary treatment) in 2006, reducing its discharge of ammonium. The change in ammonium concentrations at this station in 2006 is clearly evident in **Figure 6.**
- *Increasing trends were detected for dissolved orthophosphate (PO_4) at stations in the Central Delta.* The trend was statistically significant at one station (MD10), with an increase of more than 4% per year. The increase of PO_4 is potentially associated with the extended drought conditions in the most recent years. However, the PO_4 concentrations at this site are quite low. The detected increase is small in absolute terms and probably not meaningful.

Dissolved Oxygen (Figure 31)

- *A significant increase in dissolved oxygen was detected in the San Joaquin River at Buckley Cove (P8).* The increase in oxygen at this station (of about 1% per year) could be related to implementation of the Dissolved Oxygen Total Maximum Daily Load (DO TMDL) in the Lower San Joaquin River including Stockton WWTP upgrades (2006) and operation of aerators at Port of Stockton (began 2013) (McConnell et al., 2015).

Chlorophyll-a (Figure 31)

- *Mixed trends in chlorophyll-a.* It is difficult to draw conclusions based on the time series data for chlorophyll-a in the Delta. Generally low concentrations are punctuated by sporadic blooms. Over the 16-year period, there was a statistically significant increase in chlorophyll-a in the Confluence (D4), at one Suisun Bay station (D7), and one Central Delta station dominated by Sacramento River water (D19). There is not enough information on all the factors controlling phytoplankton blooms to speculate on the causes of the increases (1% to 3% per year) at these stations. On the other hand, there were significant decreases in chlorophyll-a in the San Joaquin River at Buckley Cove (P8, 6% per year) and in Disappointment Slough (MD10, 2% per year), a tidal backwater channel dominated by San Joaquin River water. Both stations are downstream of the Stockton WWTP. The decrease in chlorophyll-a, especially at Buckley Cove, could be due to the treatment process upgrades that were implemented at the plant in 2006.

Prior to this report, the most recent assessment of trends was from Novick et al. (2015). In that report, trends were evaluated for the period 1998–2013. Generally, the results of the updated analysis confirmed the direction of previously reported trends (Table 2). For example, the new analysis confirmed the declining trends for all nutrients at Vernalis on the San Joaquin River (C10) and increasing trends for dissolved orthophosphate at station MD10. However, at all other stations, the new data negated most of the previous observations of statistically significant declining trends in nutrient concentrations. Only in a few isolated instances were declining trends still statistically significant: ammonium is declining at station P8 on the San Joaquin River and dissolved orthophosphate is decreasing at stations D7 and D8 in Suisun Bay. The new analysis also changed the pattern of observed trends in chlorophyll-a. New increasing trends were detected for stations D19, D7, and D4. The previous analysis had not found any statistically significant increasing trends, only declining trends at stations P8 and MD10.

Another interesting observation is that the magnitudes of trends that were detected are consistent with expectations based on previous power analyses. Jabusch et al. (2016) determined that the DWR-EMP monitoring design is capable of detecting changes on the order of 50% over 10 years, or 4% per year. The statistically significant trends observed in the most recent 16-year period were all greater than 3% per year. Comparison of the actual and predicted statistical power for trend detection is helpful to validate the results of the power analyses.

Trends for the Recent Drought Years (Water Year 2012–2016)

The flow-adjusted Seasonal Kendall Test did not detect any significant trends in the most recent 5-yr period extending from WY2012 to WY2016 (**Figures 32** and **33**). However, there is a consistent pattern of positive (but not significant) trends for dissolved orthophosphate at all stations during this period, which is consistent with apparent trends evident in the time series (**Figures 16–18**).

Table 2. Observed trends in inflow-adjusted concentrations of NH_4, NO_3, DIN, TN, PO_4, and Chl-a for two time periods, calculated using Seasonal Mann–Kendall Test.

Statistically significant trends ($p \leq 0.05$) are in bold and shaded (blue = negative trend, yellow = positive trend). Values shown are annualized trends in percent change per year.

Station	Ammonium (NH_4)		Nitrate (NO_3)		Dissolved Inorganic Nitrogen (DIN)	
	1999–2013	WY 2001–2016	1999–2013	WY 2001–2016	1999–2013	WY 2001–2016
C10	–4.0	+0.4	**–3.1**	**–4.4**	**–3.3**	**–4.4**
P8	**–12.1**	**–4.4**	–0.7	–1.6	**–2.2**	–3.0
MD10	–2.2	+0.2	**–2.8**	–2.2	**–2.9**	–1.79
D26	**–2.3**	–1.6	–0.5	–0.3	–0.9	–0.8
D19	–2.8	–0.01	–3.5	–1.9	–3.5	–1.8
D28	**–1.7**	+0.08	–2.4	–2.4	**–2.2**	–2.1
D6	–0.6	–0.5	+0.4	+0.1	+0.1	–0.1
D7	**–1.3**	–1.00	–0.2	–0.3	–0.4	–0.5
D8	–1.0	–0.5	–0.3	–0.4	–0.5	–0.6
D4	**–1.7**	–1.0	–0.7	–0.7	–0.9	–1.0
C3	**–0.9**	–1.1	+1.2	+0.8	–0.5	–0.6

Station	Total Nitrogen (TN)		Dissolved Orthophosphate (PO_4)		Chlorophyll-a (chl-a)	
	1999–2013	WY 2001–2016	1999–2013	WY 2001–2016	1999–2013	WY 2001–2016
C10	**–2.7**	**–3.1**	**–2.9**	**–3.3**	+1.7	+0.3
P8	**–2.1**	–2.6	–0.1	+1.3	**–8.0**	**–6.0**
MD10	**–1.6**	–0.9	**+3.2**	**+4.3**	**–2.8**	**–1.5**
D26	–0.4	+0.1	–0.3	+0.4	–0.3	+1.3
D19	–2.3	–0.1	–0.9	+1.0	+3.5	**+2.8**
D28	**–1.6**	–0.8	0.0	+0.8	**–3.7**	–0.5
D6	–0.2	+0.5	–0.8	–0.4	+0.9	+0.9
D7	–0.6	–0.4	**–1.3**	–0.5	+0.6	**+1.3**
D8	–0.7	–0.1	**–1.4**	–0.3	+0.3	+0.9
D4	–1.0	–0.3	–1.2	–0.2	+0.9	**+1.3**
C3	–0.5	+0.1	–0.9	–0.2	+0.6	–0.6

Analysis of Nutrient Concentrations by Season during Wet and Dry Years

The previous sections evaluated whether adding the most recent data changed our understanding of recent trends in concentrations. For this section, the goal is to compare the nutrient concentrations in wet and dry years during the 16-year period. The comparison will be made on monthly concentrations in order to control for the season variability in the concentrations.

A simple conceptual model of the expected difference is that higher nutrient concentrations would be expected during the dry years because there would be less dilution. Similarly, the increase should be more pronounced in the vicinity of point sources of nutrients and during the wet season because the dry season conditions (especially later in the dry season) are similar in all years.

Figures 34 to Figure 39 show the distributions of monthly concentrations of nutrients, nutrient-related parameters, and nutrient ratios observed between years that were classified by DWR as "wet" or "above normal" versus those classified as "below normal", "dry," and "critical." Statistically significant differences in concentrations were determined using the Kruskal-Wallis Test with a significance threshold of $p < 0.05$. The statistically significant differences are highlighted on the figures with colored boxplots.

Delta inflow over the water 2001 to 2016 period is plotted in **Figure 40.** This figure also lists the Water Year Hydrologic Classification Indices for the Sacramento and San Joaquin that were assigned for each year (DWR 2017). We noted some discrepancies between the flow data and DWR's classifications. For example, WY2004 was classified as "below normal" and "dry" but the volume of Delta inflow was the same as in WY2003, which was classified as "above normal" and "below normal". The reason for the discrepancies is that the classification indices are assigned assuming unimpaired flow, whereas the inflows include discharges from water management operations. We used the hydrologic classification indices to determine "wet" and "dry" years. The years classified as "wet" or "above normal" are WY 2003, 2005–06, 2010–11 ($n = 5$). The years classified as "below normal", "dry," and "critical" are 2001–02, 2004, 2007–09, 2012–16 ($n = 11$). WY 2003 and WY 2010 were classified as both "above normal" and "below normal" depending the river inflow. These years were both assumed to be part of the "wet year" category. The assumptions that lead to these groupings could be revised for future analyses.

The major statistically significant differences in nutrient concentrations between recent wet and dry years are highlighted in the following sections.

Nitrogen and Phosphorus

- *Higher nitrogen and dissolved orthophosphate concentrations in Sacramento River water during dry years.* Concentrations of NO_3, DIN, and TN were higher in the spring and summer in dry years at stations from C3 (Sacramento River at Hood) down to Suisun Bay (**Figure 34**).

- Concentrations of dissolved orthophosphate were also higher in dry years at the Sacramento River and Suisun stations (**Figure 37**). Dissolved orthophosphate concentrations were higher in dry years in the Central Delta also but the concentrations in this region were very low in both types of years so this difference may not be meaningful.

Chlorophyll-a

- *Effect of water year type varied by region.* In Suisun Bay, summer chlorophyll-a concentrations decreased in dry years (stations D6, D7, D8, **Figure 37**). Conversely, there were increased chlorophyll-a concentrations at C10 (San Joaquin River at Vernalis, **Figure 39**) in dry years in the spring and summer. The other statistically significant changes were sporadic and small in magnitude.

Dissolved Oxygen

- *Lower dissolved oxygen in Suisun Bay during spring/summer in dry years.* At stations D6 and D7 in Suisun Bay, there were statistically significant decreases in dissolved oxygen, typically between April and June (**Figure 37**). The magnitudes of the decreases were less than 0.5 mg/L.

Nutrient Ratios

- The DIN:TN ratio was higher during dry years at 6 of the 11 stations in the spring and at one station in the summer (**Figure 41)**. The same pattern was seen for the PO4-TP ratio to a lesser extent: the PO4:TP ratio was higher in dry years at 1 station in the spring and summer, and at 2 stations in the fall (**Figure 42**). There were statistically significant differences in the TN:TP molar ratio, primarily in the San Joaquin River, but the direction of the change was inconsistent between the wet and dry years (**Figure 43**).

Discussion

The analysis conducted here confirms that nutrient concentrations (for both nitrogen and phosphorus) tend to be higher during dry years, particularly during the spring and summer. The largest differences between dry years and wet years were observed at stations along the Sacramento River downstream of the Sacramento Regional Wastewater Treatment Plant, a large point source. The differences between wet years and dry years persists downstream as far as Suisun Bay.

Ambient nutrient concentrations tend to be 30% to 40% lower during wet years compared to dry years. Greater dilution by freshwater inflows during wet years is one factor that might explain this observation. For example, the average concentration changes between wet and dry years for total nitrogen and total phosphorus in the Sacramento River were 31% to 34% (in January through June). The average change in inflows to the Sacramento River for these same years was 62%. This finding confirms the need to control for inflows and possibly other climate variables when evaluating the impact of management actions on nutrients. It also raises another question about why the ambient nutrient concentrations do no scale directly with changes in inflows. The difference is likely because other important factors and confounding variables were not part of this simplistic analysis. Other factors that should be explored are changes in non-point source loading from runoff, primary productivity in flooded areas during wet years, and changes in nutrient processing in the Delta between wet and dry years.

In contrast to the patterns in nutrient concentrations, the changes in chlorophyll-a and dissolved oxygen between wet and dry years are not consistent with dilution as a major factor controlling concentrations. Higher chlorophyll-a concentrations would be expected in dry years due to increased nutrients, longer residence time, and presumably clearer water. However, the opposite pattern occurred in Suisun Bay. In Suisun Bay, clam grazing is an important consumer of biomass. In wet years with higher flows and shorter residence times, the impact of grazing could be reduced. Also, overall primary productivity in the system might be higher during wet years when fringing wetlands are flooded. The only station where chlorophyll-a concentrations tended to be higher during dry years was C10 (San Joaquin River at Vernalis), which could be due to blooms upstream in the watershed being carried downstream. There are many important confounding variables that influence the linkage between nutrients and phytoplankton and dissolved oxygen (e.g., temperature, turbidity, grazing, water depth, salinity, etc.). It is beyond the scope of this report and there is not enough information in this dataset to control for these variables to resolve this question.

For this report, we have used the most recent 16-year period to assess “recent” trends. The rationale was that trends over longer periods would have little relevance to ongoing management actions and that shorter periods could be affected by climatic variability and would not have sufficient statistical power. Going forward, there should be agreement on this assumption because it is an important factor. Newer statistical methods that use local weighting of points could be an alternative solution. There are several newer techniques that could be employed, such as General Additive Models (GAMs) and Weighted Regression on Time, Discharge, and Season (WRTDS). These newer methods would allow for more covariates and factors to be explicitly modeled, which would provide greater insight into causation.

Water Year 2016 Nutrient Concentrations in Context with Previous Results

Figures 44 to 51 show the median concentrations from WY2016 compared to the WY2001-WY2016 dataset. Statistically significant trends for the last 16-years of data are also indicated on the graph. The purpose of these boxplots is to provide an "at a glance" overview of nutrient status and trends in the Delta. Most of the WY2016 data were within the average range of values for the entire 16-year period from 2001–2016, with these notable exceptions:

Phosphorus

- *Above average dissolved orthophosphate at all stations in the region.* The WY2016 median dissolved orthophosphate concentrations (ranging from 0.068 to 0.23 mg/L) were higher than the 16-year medians at all stations and above the interquartile range (exceeding the 75th percentile concentration) at most stations.

Chlorophyll-a

- *Above average chlorophyll-a in the Central Delta and the Confluence.* Median concentrations at all Central Delta stations and at the Confluence station (D4) were higher than the 16-yr medians. The median concentration in the San Joaquin River at Potato Point was above the 16-year 75th percentile for this station (median of 2.9 μg/L compared to 75th percentile concentration of 2.6 μg/L). The median values in WY 2016 were likely raised up by a large diatom bloom in the spring of 2016 extending from the Cache Slough complex to Suisun Bay, and up the San Joaquin River past Prisoner's Point (Bergamaschi 2016).

Nitrogen

- *Below average nitrate and dissolved inorganic nitrogen in the San Joaquin River.* The WY2016 median concentrations for nitrate and dissolved inorganic nitrogen (NO_3 = 0.61 mg/L, DIN = 0.64 mg/L) in the San Joaquin River at Vernalis (C10) were below the 25th percentile concentration (NO_3 = 0.86 mg/L, DIN = 0.89 mg/L).

3 Summary of Recently Completed Synthesis Reports

The purpose of this section is to summarize the relevant sections from recent synthesis reports. Below is a list of the reports that are covered.

- ***Characterizing and quantifying nutrient sources, sinks and transformations in the Delta: Synthesis, modeling, and recommendations for monitoring*** (Novick et al. 2015). An Aquatic Science Center (ASC) project, funded by the Department of Water Resources, synthesizing DWR-EMP data (2000–2011). http://www.sfei.org/documents/delta-nutrient-sources
- ***Summary and evaluation of Delta subregions for nutrient monitoring and assessment*** (Jabusch et al. 2016). ASC project, funded by Delta Science Program, analyzing IEP-EMP data (1975–2011) with a focus on spatial variability, potential subregions for nutrient modeling, and assessment, and limited characterization of long-term trends. http://www.sfei.org/documents/delta-subregionsassessment
- ***Planning and operating a high frequency nutrient and biogeochemistry monitoring network: the Sacramento-San Joaquin Delta***. USGS report, funded by the Delta RMP, synthesizing high-frequency sensor data. (Kraus et al., 2017; Downing et al., 2017; Bergamaschi et al., 2017).

3.1 Characterizing and quantifying nutrient sources, sinks and transformations in the delta: Synthesis, modeling, and recommendations for monitoring

Project Team

Aquatic Science Center, Research Management Associates (RMA), U.S. Geological Survey (USGS)

Funding

California Department of Water Resources (DWR)

Reference

Novick E., R. Holleman, T. Jabusch, J. Sun, P. Trowbridge, D. Senn, M. Guerin, C. Kendall, M. Young, and S. Peek. 2015. Characterizing and quantifying nutrient sources, sinks and transformations in the Delta: Synthesis, modeling, and recommendations for monitoring. San Francisco Estuary Institute, Richmond, CA. http://www.sfei.org/documents/delta-nutrient-sources

Approach

1. *Long-term monitoring data synthesis and analysis.* The goal of this study elements was to characterize seasonal, spatial, and long-term variability in nutrient concentrations and proportions. The project element consisted of the compilation, synthesis, and analysis of monthly monitoring data (1975–2013) collected by the California Department of Water Resources' Environmental Monitoring Program (DWR-EMP) at stations in the Sacramento–San Joaquin Delta and Suisun Bay (**Figure 1, Table 3**). The main N species investigated were ammonium (NH_4), nitrate (NO_3), dissolved inorganic nitrogen (DIN), and total nitrogen (TN). This study element also included a more limited evaluation of total phosphorus (TP) and dissolved orthophosphate (PO_4). Data for chlorophyll-a were graphed and tabulated but not specifically evaluated. The bulk of the work consisted of visualization, statistical analysis, and interpretation of seasonal and long-term patterns in the data. Statistical analyses included detection of trend and an evaluation of main factors driving data variability. To minimize the impact of changes in flow on trend detection, the trend analyses were performed after adjusting the data for total Delta inflow. The Mann-Kendall Test was used to detect seasonal trends and the Seasonal Kendall Test to detect long-term trends. An empirical orthogonal functions (EOFs) analysis was used to reveal visually whether there are similarities and differences in factors driving variability in concentrations across stations, and changes in the significance of

these factors over time. Most of the statistical analyses were done using the R software.

2. *Mass balance modeling*. This project element applied a hydrodynamic model (the Delta Simulation Model 2, or DSM2) to establish a mass balance and quantify nutrient loads of NH_4, NO_3, DIN, and TN to and from the Delta. It also applied the DSM2 nutrient model to characterize and quantify nitrogen transformations and losses during transit through the Delta under a range of flow conditions.
3. *Isotope data analysis*. This project element consisted of an evaluation of existing stable isotope data collected at sites in the Delta and its tributaries. The objective was to obtain additional information about dominant processes controlling the fate of nitrogen in the Delta. For example, isotope data analysis can help determine if spatial gradients in nutrient concentrations are most likely caused by chemical transformation, uptake by plankton, or burial in the sediment.

Key Findings

Seasonal and temporal changes in nutrient concentrations

The synthesis report documents a large degree of temporal and spatial variability across stations. **Figure 52** represents the range of spatial and seasonal patterns observed in NH_4, NO_3, DIN, and TN. Stations. Stations in the inner Delta can have typical summertime DIN depletion, whereas seasonal variability at upstream stations on the Sacramento and San Joaquin rivers does not follow this pattern because it is affected by upstream loadings and local sources.

A trend analysis of the entire 38 year data record from 1975–2013 showed significant increasing trends for nitrogen species and significant decreasing trends for PO_4 at most of the stations. However, if only the data from the most recent 15-year period from 1998 to 2013 are analyzed, there is a change in the direction of trends for the nitrogen species. For the period from 1998 to 2013, there are significant decreasing trends in ammonium at six of 11 stations, and no trends at the remaining five stations. Similarly, there are significant decreasing trends for nitrate at two stations, and no trends for nitrate at the other stations for the period from 1998 to 2013. Dissolved orthophosphate declined during the 38 year period from 1975–2013 at 9 of 11 sites and also declined at 4 sites during the period from 1998 to 2013, but there was also an increasing trend at one of the stations (MD10, Disappointment Slough) for the period from 1998 to 2013. Generally, and not surprisingly, the trends are more consistent across stations as the length of the analyzed period increases.

The trend analysis revealed that extrapolation across space may be problematic. For the shorter period of 1998–2013, seven of the eleven stations did not have any significant correlations in trends across multiple variables with any other station. More specifically, variables exhibit rather unique patterns of trends at each of these stations.

The report concludes that existing stations are not redundant (with the exception of the Suisun Bay stations), because trends for several stations were not consistent with each other over time and variables exhibit rather unique patterns of trends and variability. It follows that conditions and trends at the currently monitored stations cannot be extrapolated to areas of the Delta that are not currently monitored, such as the North Delta, the South Delta, and contributions from Eastside tributaries. Additional stations would be needed, if the goal were to evaluate conditions and trends across all regions of the Delta. Given the large amount of variability associated with flow and temperature, these ancillary variables should also be measured at water quality stations.

Mass balance for nitrogen

The mass balance estimates suggest that the Delta functions as an important biogeochemical reactor, where significant transformation processes occur at a large scale. The results of the mass balance analyses are represented in **Figures 53 and 54.** These results suggest that the majority (65%–85%) of NH_4 that entered the Delta during summer months did not leave the system as NH_4, and must therefore have undergone nitrification[3] or been assimilated by organisms. In addition, 25% of TN loads to the Delta were lost during summer months. Realistic estimates of denitrification[4] and accumulation/burial rates within the Delta can combined readily explain the TN losses.

The analysis further revealed that processes affecting nutrient concentrations, loadings, and losses vary strongly across subregions of the Delta. The six subregions used in the DSM2 model calibration had markedly different NH_4 and TN losses, both in terms of actual mass lost and proportional loss (relative to input to that subregion), as illustrated in **Figure 54**. In four of the six Delta regions more than half of the ammonia that entered the region was lost. Losses were approximately 20% in the Southern region and 40% in the Confluence regions. The greatest NH_4 loss (mass and percentage) occurred in the North region, followed by the East. Total nitrogen (TN) losses were greatest in the North (2,900 kg/d; 10%), Central (5,500 kg/d; 25%) and South regions (2,600 kg/d; 15%), and smaller in the East, San Joaquin, and Confluence regions.

[3] Nitrification: a process aided by bacteria where ammonia (NH_3) or ammonium ions (NH_4^+) are converted to nitrite (NO_2^-), after which nitrite is oxidized to nitrate (NO_3^-).

[4] Denitrification: a process aided by bacteria where nitrate ions (NO_3^-) are reduced and converted to other nitrogen compounds, ending finally as molecular nitrogen (N_2).

Isotopic evidence for transformations

The analysis of isotopic data confirmed that nitrification is occurring throughout the Delta, particularly along the Sacramento River corridor. In addition, the results from this analysis suggest that less nitrification occurred during high flow periods. The results also provide some evidence that nitrogen uptake by phytoplankton may be a dominant process in the system, although a full mass balance to test this theory is still underway.

Significance

- *Trends within subregions*. The results from this study suggest that seasonal and long-term trends vary considerably between and within subregions of the Delta.
- *Important processes.* The Delta acts as a giant "biogeochemical" reactor were large scale transformations of nutrients entering the system occur. Much of the NH_4 entering the system seems to gets transformed to NO_3 or assimilated by organisms. A significant portion of total nitrogen entering the Delta appears to get either lost to the atmosphere by denitrification of NO_3 to gaseous N_2 or buried in sediment. Loadings and dominant processes vary significantly across subregions. Some subregions are net sources and others are net sinks for different nitrogen forms.
- *Forecasting.* Reliable forecasts of ambient conditions require models that can accurately account for losses and transformations under current conditions and respond in realistic ways to changes in physical and chemical drivers. More targeted modeling work is needed to identify areas where the greatest losses occur, and to understand the relative importance of factors contributing to those losses, such as flow routing, residence time, and temperature.

Table 3. List of DWR-EMP discrete water quality stations included in the analyses presented in Novick et al. (2015).

Station Code	Location	Subregion
C3	Sacramento River @ Hood	Sacramento River
D26	San Joaquin River at Potato Point	North Central Delta
MD10	Disappointment Slough @ Bishop Cut	North Central Delta
P8	San Joaquin River @ Buckley Cove	North Central Delta
D19	Frank's Tract	South Central Delta
D28A	Old River @ Rancho Del Rio	South Central Delta
C10	San Joaquin River near Vernalis @ SJR Club	South Delta
D4	Sacramento River above Point Sacramento	Confluence
D6	Martinez	Suisun Bay
D7	Grizzly Bay	Suisun Bay
D8	Suisun Bay off Middle Point near. Nichols	Suisun Bay

3.2 Summary and evaluation of Delta subregions for nutrient monitoring and assessment

Project Team

Aquatic Science Center

Funding

Delta Science Program

Reference

Jabusch T., P. Bresnahan, P. Trowbridge, A. Wong, M. Salomon, and D. Senn. 2015. *Summary and Evaluation of Delta Subregions for Nutrient Monitoring and Assessment*. Aquatic Science Center, Richmond, CA. http://www.sfei.org/documents/summary-and-evaluation-delta-subregions-nutrient-monitoring-and-assessment

Approach

The Delta Science Program provided funding to ASC to synthesize nutrient data and analyses to identify options for optimizing the design of a status and trends nutrient monitoring program for the Delta. Specific goals were to:

1. Summarize, compare, and recommend potential subregions to be used for monitoring and assessing nutrients in the Delta;
2. Investigate spatial and temporal patterns in nutrient trends and potential drivers of these patterns relative to proposed subregions;
3. Evaluate if the current nutrient monitoring design is sufficient to characterize nutrient status and trends in proposed subregions; and
4. Assess the current monitoring coverage of different aquatic habitat types within each of the proposed subregions.

This work was conducted under the assumption that a status and trends monitoring program for nutrients in the Delta should cover all distinct subregions and representative habitats, and be able to detect trends of ecological and management interest. Based on this assumption, the report identifies limitations of the current monitoring efforts and detailed options for improving the nutrient monitoring program based on a careful review of existing data. For water quality data, this effort focused primarily on the multi-decade monthly monitoring data collected by DWR-EMP and on a few examples of high-frequency data.

Key Findings

1. **Changing the way subregions are delineated could improve our understanding of nutrients across the Delta.** The study identified seven potential subregions to distinguish among areas where distinct physical and biogeochemical drivers influence nutrient dynamics or nutrient-related responses. The proposed subregions are (**Figure 1**; from north to south): Sacramento River, North Delta, Eastside, Suisun Bay, Central Delta, Confluence, and South Delta. The proposed subregions are derived from operational landscape units (OLUs), which are a newly developed planning tool for landscape-scale ecosystem restoration in the Delta (Grenier and Grossinger 2013). The OLU delineations are based on ecosystem functions and physical drivers such as water source and hydrology; therefore, there is a mechanistic linkage and scientific foundation for their use in the context of nutrient conditions and cycling. The review also concluded that the proposed subregions are compatible with the DMS2 hydrologic model and in general agreement with water quality regions used by major monitoring programs. *Note:* in preparing some more recent modeling work described in the Delta RMP Nutrients Modeling report (Jabusch et al. 2017), the Central Delta is further divided into North Central Delta and South Central Delta to better characterize regional differences in water source and reduce model uncertainty. This subdivision is expected to facilitate the interpretation of nutrient monitoring results.

2. **Trends in nutrient concentrations, and the processes that affect nutrient concentrations, vary across the proposed subregions**. A statistical time-series analysis was employed to characterize nutrient variability within and across subregions of the Delta and assess similarities and differences in underlying drivers. The employed method was non-negative matrix factor (NMF) analysis, which was chosen because it facilitates physical interpretation of detected factors as potential drivers of variability.

   This part of the study examined patterns of variability in nutrient concentrations and relevant ancillary data both across subregions, and, when possible, within subregions. The results from the NMF analysis suggest that there are significant differences in the relative importance of underlying drivers of nutrient cycling across subregions, which supports the notion that these subregions are indeed distinct from the perspective of nutrient cycling and ecosystem response to nutrients. The NMF analysis detected considerably different patterns of variability for nutrient-related parameters between Central Delta stations, suggesting there are important differences in the relative strength of underlying drivers of nutrient cycling. In contrast, Suisun Bay was found to be a rather homogeneous subregion, with similar patterns of variability observed at all three stations. Absolute nutrient concentrations did differ between Suisun stations; but both the timing and the relative magnitude of variability were similar. The patterns for the Confluence and South Delta were intermediate between the strong heterogeneity observed in the Central Delta and the strong homogeneity among Suisun stations. The spatial variability in the Confluence and South Delta subregions appears to occur mostly along gradients representing flow paths (e.g., in the Confluence subregion along the Sacramento River) or gradually changing peripheral influences (e.g., transition from Sacramento to San Joaquin River influence).

Spatial variability within the Sacramento River, North Delta, and Eastside subregions could not be evaluated, because there is only one DWR-EMP water quality monitoring station in the Sacramento River subregion and none in the North Delta and Eastside subregions.

3. **The current monitoring design is insufficient to characterize nutrient status and trends across the Delta**. We performed historical trend analysis and statistical power analysis to evaluate the capability of the current monitoring network to detect long-term trends. The historical trend analysis examined if trends were detected with DWR-EMP monitoring data. The power analysis evaluated whether increasing the number of stations or the sampling frequency will significantly improve our ability to detect seasonal, temporal, and spatial trends. A key assumption for this analysis was that the DWR-EMP would continue to serve as a core program for the collection of regional monitoring data for nutrients. We specifically examined (a) if trend detection could be improved by resuming monitoring of discontinued stations; and (b) if continuous sensor monitoring could provide better long-term trend detection capabilities than discrete monthly grab sampling.

   A general observation is that the current DWR-EMP sampling does not cover all proposed subregions, and thus, cannot be considered sufficient to characterize nutrient status and trends in all subregions. There are currently no DWR-EMP sampling stations in the North Delta and the Eastside. The U.S. Geological Survey (USGS) has installed 5 moored sensors in the North Delta that are generating data since August 2013 (see Section 3.3 for additional details). However, these sensors do not completely fill the gap, because they currently only measure nitrate and none of the other nutrient variables, such as ammonium or dissolved orthophosphate. Other programs are monitoring nutrients at stations located in the North Delta and Eastside, but their monitoring is currently not coordinated with the DWR-EMP in terms of parameters analyzed, frequency and timing of sampling, and comparability of data.

4. **Adding more discrete monitoring sites could improve the ability to detect regional or sub-regional long-term trends for some water quality parameter**s. In historic trend analyses (using regional Kendall tests), results were nearly identical when active sites and all sites (active plus discontinued, pre-1995 data) were tested (**Figure 55**). Although one potential interpretation of this comparison is that the discontinued stations would not have influenced our interpretation of trends, power analysis results provide a different perspective. The power analysis, based on an assumed criterion of detecting a 50% change over 10 years, suggests that monthly water quality monitoring should be resumed at some of the deactivated stations in order to have sufficient statistical power to detect trends for ammonia and chlorophyll-a in some subregions (**Figure 56**).
5. **Strategically placed high-frequency sensors could significantly improve trend detection capabilities** for those parameters for which reliable sensors are available, such as chlorophyll-a and nitrate (**Figure 57**). This observation is a result of the power analysis described above. Because sensors do not capture all the variables of interest, monthly water quality sampling sites should be co-located with continuous sensors.
6. **Current monitoring activities do not cover some important aquatic habitat types.** The study included a rough overlay of existing monitoring stations with four habitat categories: deep water, shallow water, dead-end sloughs, and wetland/riparian. This preliminary evaluation suggests significant data gaps in terms of aquatic habitat coverage. By design, current monitoring does not evenly cover all aquatic habitat types. Critically, there are currently no programs to systematically monitoring nutrients in Delta wetlands. Further, there is no systematic monitoring of dead-end sloughs and shallow margin areas.

Significance

- *Subregions.* Eight subregions (Sacramento River, North Delta, Eastside, Suisun Bay, North Central Delta, South Central Delta, South Delta, Confluence, and Suisun Bay) provide a good starting point for status and trends monitoring of nutrient-related parameters. The existing DWR-EMP monitoring program has at least one station in 6 of these 8 regions but only in the deep-water habitats, not wetland areas.
- *Trend detection.* The existing monthly monitoring program can, in general, detect a trend of 50% change over 10 years for most parameters investigated here. A

50% change in a water quality parameter represents a large change in ecosystem condition, and it may be necessary or desirable to identify smaller trends.

- *Recommendations.* Improved trend detection appears possible through well-planned placement of sensors for nitrate, chlorophyll-a, and possibly other parameters that can be measured with high-frequency in-situ sensors. To best capture nutrient variability and trends across and within proposed subregions, a sensor network and a discrete sampling program should be planned to complement each other. Modeling, advanced statistical analyses, and targeted monitoring should be used to plan and optimize the monitoring program.

3.3 Planning and operating a high frequency nutrient and biogeochemistry monitoring network: the Sacramento-San Joaquin Delta

Project Team

USGS California Water Science Center (CAWSC) Biogeochemistry Group

Funding

Delta Regional Monitoring Program

References

Kraus T.E.C., B.A. Bergamaschi, and B.D. Downing. 2017. *An introduction to high-frequency nutrient monitoring for the Sacramento-San Joaquin Delta, northern California*. U.S. Geological Survey Open File Report 2017-5071. U.S. Geological Survey, Reston, Virginia. https://pubs.er.usgs.gov/publication/sir20175071

Downing B.D., B.A. Bergamaschi, and T.E.C. Kraus. 2017.*Synthesis of high-frequency nutrient and associated biogeochemical monitoring in the Sacramento-San Joaquin Delta, northern California*. U.S. Geological Survey Open File Report 2017-5066. U.S. Geological Survey, Reston, Virginia. https://pubs.er.usgs.gov/publication/sir20175066

Bergamaschi B.A., B.D. Downing, T.E.C. Kraus, and B.A. Pellerin. 2017. *Designing a high-frequency nutrient and biogeochemistry monitoring network: the Sacramento-San Joaquin Delta, northern California*. U.S. Geological Survey Open File Report 2017-5058. U.S. Geological Survey, Reston, Virginia. https://pubs.er.usgs.gov/publication/sir20175058

Approach

With funding from the Delta RMP, scientists from the USGS CAWSC Biogeochemistry Group prepared a series of three reports that provide information about high frequency (HF) nutrient and biogeochemical monitoring in the Sacramento-San Joaquin Delta. The first report in the series (Kraus et al. 2016) provides an introduction for how high frequency measurements currently are being used in the Delta to examine the relationship between nutrient concentrations, nutrient cycling, and aquatic habitat conditions. The second report (Downing et al. 2016) synthesizes data available from the nutrient and water quality monitoring network currently operated by the USGS in the North Delta and Sacramento River subregions (**Figure 58**). The review focused on HF data of nitrate (mg/L-N), DO (mg/L), and chlorophyll-a (µg/L) concentrations collected at the USGS water quality stations in the Delta over two water years; WY2014

(10/1/2013–9/30/14) and WY2015 (10/1/2014–9/30/15) to identify important timescales of variability. These two water years include the greatest number of stations, allowing to assess regional patterns. The third report in the series (Bergamaschi et al. 2016) provides information about how to design high frequency nutrient and biogeochemical monitoring for assessment of nutrient inputs and dynamics within the Delta. The third report also includes three example nutrient monitoring network designs for the Delta and discusses how they would address high priority questions identified by the Delta Regional Monitoring Program.

Key Findings

1. Attributes of a High Frequency Nutrient Monitoring Network for the Delta (from Kraus et al. 2016)

ATTRIBUTES OF A HIGH FREQUENCY NUTRIENT MONITORING NETWORK FOR THE DELTA

HIGH FREQUENCY (HF): In tidal systems, measurements must be made at least once every 15-20 minutes.

CONTINUOUS: Data are collected continuously over an extended period (months-years) of time.

REAL TIME: Data are delivered to users in real time, facilitating decision making by managers, improving data quality and acting as a trigger for additional data collection efforts. *Data collected in the Delta are available at* http://waterdata.usgs.gov/nwis.

FIUX BASED: Simultaneous collection of flow data permits calculation of mass fluxes and loads. *Most current nutrient stations in the Delta are co-located with the Delta's Flow-Station network (http://dx.doi.org/10.3133/fs20153061).*

MULTI PARAMETER: Simultaneous collection of related water quality parameters improves understanding of nutrient sources, sinks, processing, and effects. *In the Delta, stations that are equipped with nitrate sensors also measure temperature, pH conductivity, dissolved oxygen, turbidity, fluorescence of dissolved organic matter, chlorophyll-a fluorescence and blue-green algal fluorescence.*

NETWORK: Stations are spatially distributed so that sources, transport, and fate of nutrients can be tracked and their effects on Delta habitats can be assessed at multiple spatial scales.

For details see Kraus et al. (2016)

2. *Seasonal, inter-annual and spatial variability in monthly averages.* To assess seasonal water quality patterns and related spatial patterns in the Delta, the HF data was aggregated for each station by month (Figure 59).

A. *Nitrate.* The authors observed that concentrations were generally lower in the Sacramento River at Freeport (FPT), increasing downstream to the lower Sacramento River at Decker Island (DEC). Concentrations of nitrate are generally higher at the North Delta sites (LIB, CCH, LCT, TOE) and presumably reflective of nitrification of wastewater-derived ammonium as well as inputs of nitrate from upstream sources during storm events (Kendall et al. 2015). Highest concentrations were generally observed in the winter in association with storm events and higher flows, but the timing of the peaks is different between stations; the highest concentrations at Freeport and Walnut Grove occur days or weeks earlier than those at stations in the North Delta and Confluence (DEC). The lowest concentrations occur in late summer corresponding to the peak in the annual cycle of temperature, which may be a reflection of higher rates of biologically driven nutrient uptake and denitrification. These general trends are the same as found by Novick et al. (2015), whose results are described in Section 3.1.

B. *Chlorophyll-a.* Chlorophyll-a fluorescence (Chl-a) exhibited seasonal, inter-site, and inter-annual variability Chl-a tended to be higher in the winter and early spring in the upper Sacramento River (FPT, WGA) and the far northern Delta sites (TOE, LIB). The large channel sites–CCH and DEC–had generally lower Chl-a concentrations. A substantial within-month range in concentrations was observed at most sites, indicating that monthly sampling has limited validity. Higher Chl-a concentrations were not always associated with higher nitrate concentrations. The authors point out that the relationship between nitrate and Chl-a is inter-related. While phytoplankton require N for primary production, they also draw down the nitrate concentration. The authors further advise that a predictable pattern of high nitrate followed by high Chl-a and nitrate drawdown is not necessarily to be expected, due to the complex hydrodynamics in the Delta, variability in grazing rates by zooplankton and other herbivores, and other factors.

C. *Dissolved Oxygen.* For DO, the authors report a clear seasonal signal, owing to the temperature-dependent solubility of oxygen, seasonal biological processes, and hydrodynamic changes. DO concentrations dip from about 10 mg/L during winter and spring to a summer pattern of around 8.0 mg/L. Nevertheless, some sites showed marked deviation from this seasonal pattern, evident even at the monthly time step. This suggests that other processes that produce oxygen (photosynthesis) or that consume oxygen (respiration, decomposition, and nitrification) are dominant controls on DO concentrations at these sites. Sites in the northern Delta (LCT, TOE) showed values lower than the seasonal change would suggest, indicating that DO was depressed for months at a time. These DO sags are interesting in that these events may indicate seasonal changes in water residence time associated with low flow in the north Cache Slough Complex, specifically in the stair-step levee region. Conversely, LIB, CCH and DEC were generally greater in summer, suggesting increased net primary production.

3. Seasonal, inter-annual and spatial variability in HF time series.

Individual HF time series (**Figure 60**) demonstrate how highly resolved time series are critical to accurately quantify the rate and magnitude of changes in nitrate concentration due to storms and other drivers of rapid change. Rapid shifts in nitrate concentration were observed during winter and spring precipitation events at all stations in both WY2014 and WY2015; peaks seen in the continuous nitrate data are not evident in the monthly aggregated data (**Figure 59**) and were not captured in the grab sample-based monitoring. The response in nitrate concentration to storm activity is distinctly different between stations. The assessment also demonstrated periodic variability related to diurnal tides (e.g. single high and single low tide per tidal day); semidiurnal tides (e.g. two high and two low tides each tidal day); and diel (solar radiation 24 hour period) cycling. The effects of tides are different between stations.

4. Loads and Fluxes.

Annual loads for nitrate, chlorophyll-a, and dissolved oxygen concentrations were determined by summing the product of the instantaneous discharge (Q) and concentration (i.e., flux data, measured every 15 minutes) continuously over a water year (Downing et al. 2009). Note that the cumulative flux is the continuous expression of the integrated flux over time as the year progresses, while the annual load is the value of the cumulative flux at the end of the year. The trend in the cumulative flux of a constituent can be positive, indicating net movement is seaward, or negative, indicating net movement is landward.

A. *Nitrate.* For WY2014 and WY2015, annual nitrate loads calculated for all eight stations ranged from about 1,000 to 5,000 metric tons (**Figure 61**). Step increases in the cumulative flux are related to precipitation events and account for approximately 30% to 40% of the measured annual load. An interesting observation is that annual loads were highest at the Confluence station compared to the other seven stations, especially considering the relatively low annual load at CCH (which is about 1 tidal excursion upstream of DEC) in both water years; this will require further investigation. Because nitrification of ammonium cannot reasonably account for this increase, the authors hypothesize that there may be unaccounted inputs of nitrate from the San Joaquin River and/or Central Delta via Three Mile or the Confluence that serve as subsidy to the larger fluxes seen at Decker Island.

B. *Chlorophyll*-a. Annual loads of chlorophyll-a range from 3 to 25 metric tons, with the lowest chlorophyll-a load found at CCH and the highest at FPT (**Figure 61**). Decreases in chlorophyll-a during transport down the Sacramento River have been observed in previous studies and are subject of current investigation (e.g.: Foe et al. 2010, Kraus et al. 2017). The annual chlorophyll-a load at DEC was also greater and, like nitrate, may be the result of unaccounted inputs from Three Mile slough or the Confluence.

C. *Dissolved Oxygen.* Annual loads of DO range from 8,000 to 80,000 metric tons, with the highest loads measured at Freeport and lowest measured at Cache Slough in both WY2014 and WY2015.

D. *Advective vs. dispersive flux.* One benefit of HF time series data is that it is possible to examine the difference between the advective flux—the constituent flux driven by movement of water in one direction, such as in a river—and the dispersive flux—the flux driven by mixing of water with different constituent concentrations. Traditional methods for calculating constituent fluxes typically use a monthly or flow-weighted median concentration value, which only accounts for the advective flux. Separating the advective flux from the total flux past the site in Cache Slough (CCH) reveals that the advective flux of nitrate is only about 70% of the total nitrate flux, meaning that traditional methods would underestimate the total by about 30%.

5. Example network plans.

The third report in the series (Bergamaschi et al. 2016) describes three network examples to provide illustrations of how to plan and evaluate potential high-frequency (HF) network designs of different capabilities and costs, and to compare their utility. The three examples provided below are intended to help foster the types of discussion needed to establish a realistic plan.

A. *Example Network #1*. Best addresses Assessment Questions SPLP-1 and SPLP-1B; partially addresses ST-1, ST-1B, and SPLP-1G; and provides information for FS-1. Because only inputs and outputs are monitored, this example leaves important data gaps associated with subregions of the Delta (ST-1C). The data will be primarily useful for managers seeking to document the efficacy of nutrient reduction efforts such as Total

Maximum Daily Loads (TMDLs) and best management practices (BMPs), for establishing trends in nutrient loads to the Delta, and for evaluating changes in timing of those loads. Estimated initial costs: $566,318. Estimated operation and maintenance (O&M) costs: $474,453 per year. This network is summarized in Table 4 and Figure 62.

Table 4. Three stations proposed as part of HF monitoring network example #1.

Station Name	Station ID	Station primary purpose
San Joaquin River at Stockton	SJG (C)	Monitor fluxes and loads from San Joaquin Valley and Stockton wastewater treatment facility.
Sacramento River at Walnut Grove above Georgianna Slough	SDC (A)	Monitor fluxes from Sacramento Valley and Sacramento storm discharge and Sacramento wastewater treatment facility.
Cache Slough at Ryer Island	RYI (B)	Monitor fluxes from Yolo Bypass. Miner Slough and Cache Slough

B. *Example Network #2*. Best addresses Assessment Questions ST-1, ST-1A, ST-2, and SPLP-2C; partially addresses ST-1B, ST-2A, SPLP-1A, SPLP-1E, and SPLP-1F. The data will be useful for managers seeking to document the persistence, transit times, and effects of nutrients in the Delta, for establishing trends in nutrient loads internal to the Delta, and for relating nutrient concentrations within the Delta to flows and exports. Because tributary inputs and outputs are not included, and the spatial distribution of stations in the central Delta is minimal, this example does not allow assessment of the importance of different nutrient sources (SPLP-1, SPLP-1D, SPLP-1G) and leaves important data gaps associated with sub-regions of the Delta (ST-1C). Estimated initial costs: $1,042,636. Estimated operation and maintenance (O&M) costs: $852,906 per year. This network is summarized in Table 5 and Figure 63.

Table 5. Six stations proposed as part of the high-frequency monitoring network example #2.

Station Name	Station ID	Station Primary Purpose
Sacramento River at Rio Vista	SRV (A)	Monitor nutrient concentrations and fluxes in Sacramento River
Jersey Point	SJJ (B)	Monitor nutrient concentrations and fluxes in the San Joaquin mainstem. Assess contributions from Central Delta Islands
Old River	OH4 (F)	Assess nutrient by mass balance contributions from Central Delta Islands
Middle River	MDM (E)	Assess mass balance contributions from Central Delta Islands
Middle River near Holt	HLT (D)	Assess exchange contributions from Central Delta Islands
Old River at Franks Tract	OSJ (C)	Assess exchange contributions from Central Delta Islands

C. *Example Network #3*. This example network addresses the broadest range of the Assessment Questions listed in Table 1, although there may still remain data gaps associated with specific subregions of the Delta (ST-1C) that will require targeted monitoring efforts. The data will be useful for managers seeking to document the persistence, transit times, and effects of nutrients in the Delta, for establishing trends in nutrient loads internal to the Delta, and for relating nutrient concentrations within the Delta to flows and exports. Because tributary inputs and outputs are not included, and the spatial distribution of stations in the central Delta is minimal, this example does not allow assessment of the importance of different nutrient sources (SPLP-1, SPLP-1D, SPLP-1G) and leaves important data gaps associated with sub-regions of the Delta (ST-1C). Estimated initial costs: $2,991,908. Estimated operation and maintenance (O&M) costs: $2,313,718 per year. This network is summarized in Table 6 and Figure 64.

Table 6. Eighteen stations proposed as part of HF monitoring network example #3.

Station Name	Station ID	Station Primary Purpose
Sacramento River at Freeport	FPT (A)	Monitor fluxes from San Joaquin Valley
Yolo Bypass at Toe Drain	TOE (B)	Resolve fluxes at Cache Slough from Yolo Bypass
Shag Slough	SHG (R)	Observe concentrations and fluxes in long-detention-time areas of the North Delta
Sacramento River at Walnut Grove above Georgianna Slough	SDC (D)	Monitor fluxes from Sacramento Valley and Sacramento stormwater discharge and Sacramento wastewater treatment facility. Assess rates in Sacramento River.
Liberty Island	LIB (C)	Monitor interactions with shallow water areas of Liberty Island
Cache Slough at Ryer Island	RYI (E)	Monitor fluxes from Yolo Bypass. Miner Slough and Cache Slough
Sacramento River al Rio Vista	SRV (F)	Continuous productivity modeling in Lower Sacramento River
Decker Island	SDI (G)	Monitor concentrations and fluxes in Lower Sacramento River
Confluence	CFL (O)	Assess mass flux into San Francisco Estuary
Suisun Bay	SUI (J)	Link mass flux to conditions in Suisun Bay
Jersey Point	SSJ (I)	Monitor concentrations and fluxes on the San Joaquin mainstem. Assess contributions from Central Delta Islands
False River	FAL (K)	Assess by exchange contributions from Central Delta Islands
Old River at Frank's Tract	OSJ (H)	Assess by exchange contributions from Central Delta Islands
Old River	OH4 (L)	Assess by mass balance contributions from Central Delta Islands
Middle River	MDM (M)	Assess by mass balance contributions from Central Delta Islands
Middle River near Holt	HLT (P)	Assess by exchange contributions from Central Delta Islands
San Joaquin River at Stockton	SJG (N)	Monitor fluxes from San Joaquin Valley and Stockton wastewater treatment facility
San Joaquin River at Vernalis	SJR (Q)	Monitor fluxes from Sacramento Valley and Sacramento stormwater discharge and Sacramento wastewater treatment facility.

Significance

- *Advantages of HF monitoring.* Collection of HF data allows to more accurately quantify nutrient fluxes and loads and to understand how nutrient fate and effects are related to the periodic cycles occurring within the Delta.
- *Monitoring design recommendations.* Design of a HF network should carefully consider the current and future uses to which the HF data will be applied and how these and related data should be served to users. Further, given that HF monitoring technology is in its infancy, the network design should anticipate and build in the capacity to receive future technologies as they become available.

4 Summary of Findings to Date Regarding Delta RMP Assessment Questions

The goal of the Delta RMP is to answer the assessment questions that were established at the onset of the Program. The new analyses presented in Section 3 of this report focused on rounding out our knowledge on status and trends of nutrients and nutrient-related parameters in the Delta. The previous reports summarized in Section 4 have focused on identifying data gaps (Jabusch et al. 2016), quantifying loads (Novick et al, 2015), evaluating subregions (Appendix 2 in Jabusch et al. 2016), and evaluating high-frequency sensors (Kraus et al., 2017, Downing et al., 2017, Bergamaschi et al., 2017). The combined findings from these and other contributions constitute encouraging early progress toward answering the Delta RMP's assessment questions.

In order to assess progress toward answering the Delta RMP assessment questions, we have prepared a summary of the state of knowledge for each questions in **Table 7.** For each question, the degree to which the question can be answered has been qualitatively estimated along with a short statement that summarizes our current understanding. Key points from this table are:

- Due to the existence of long-term data sets and analyses of these presented here, regional long-term trends are reasonably well understood and so are the types and magnitudes of the most important sources, pathways, and processes. However, additional synthesis work could be done to understand the factors behind these trends. There is still some uncertainty around spatial variation within and across some subregions, including the North Delta, Northeast Delta, and large areas of the South Delta, and in specific habitat types that are currently not monitored, such as shallow water habitats, back sloughs, and wetlands.
- A major gap in our knowledge is the current status of the Delta ecosystem as influenced by nutrients. Answering this question will require establishing linkages between nutrients primary productivity, macrophytes, harmful algal blooms, and dissolved oxygen, taking other factors and confounding variables into account. Ramping up to answer these questions will take significant effort and careful planning. The Delta Nutrient Research Plan will provide the roadmap for establishing linkages.
- Large knowledge gaps remain about nutrient sinks, sources, and processes in the Delta. The mechanistic, water quality-hydrodynamic models being developed for the Delta may be able to address these questions in the future. However, the important processes, time-scales, and spatial scales need to be better defined in order to know the best way forward. Gaps in data to calibrate and validate the models will need to be addressed by augmenting existing monitoring programs

with additional parameters, stations, and sampling events (increased sampling frequency). Short-term intensive monitoring and special studies, conducted within an adaptive management framework, will be needed to test the effects of management actions, and to elucidate model mechanisms and parameterization. More importantly, tight collaboration between modelers, monitoring programs, scientists, and managers though annual meetings will be needed for the modeling effort to be successful (Trowbridge et al. 2016).

Table 7. Summary of findings to date regarding Delta RMP assessment questions.

Prioritized questions are bolded. The pie charts estimate the current level of confidence in the answer to each questions (a larger blue area means higher confidence). The level of confidence is a qualitative estimate based on professional judgment.

	Nutrient Assessment Questions	Current Knowledge	Summary
Status & Trends (ST)			
ST1	How do concentrations of nutrients (and nutrient-associated parameters) vary spatially and temporally?		Long-term trends in the water column of main channels are reasonably well understood in the areas where long-term monitoring data have been collected. Concentrations of all analyzed parameters exhibit seasonality, interannual variability, and spatial differences. The most substantial spatial differences are in the different nitrogen forms (NH_4, NO_3, DIN, and TN) and chlorophyll-a.
ST1A	Are trends similar or different across subregions of the Delta?		This report and previous synthesis reports (Novick et al. 2015, Jabusch et al. 2016) suggest that seasonal and long-term trends vary considerably between and within subregions of the Delta. Differences are well understood for subregions monitored by the DWR-EMP. Large uncertainties remain around spatial variation within and across some subregions, including the North Delta, Northeast Delta, and large areas of the South Delta. Recent efforts by DWR Municipal Water Quality Investigations (MWQI) and USGS are starting to fill some of these gaps for the North Delta and Northeast Delta.
ST1B	How are ambient levels and trends affected by variability in climate, hydrology, and ecology?		The updated data analyses presented in Section 3 of this report evaluated how climate variability affected ambient concentrations during wet and dry years. Key findings were: 30% to 40% higher concentrations of nitrogen and dissolved orthophosphate are present in the Sacramento River water during dry years. Effect of water year type on chlorophyll-a varied by region. However, additional research is needed on this topic. There are numerous other factors, including other climatic factors, that influence ambient concentrations of nutrients (see Figure 3).

	Nutrient Assessment Questions	Current Knowledge	Summary
ST1C	Are there important data gaps associated with particular water bodies within the Delta subregions?		Delta RMP reports including the 2016 Nutrient Monitoring Workshop report and previous reports produced by ASC (Novick et al. 2015, Jabusch et al. 2016) have thoroughly addressed this question. Major gaps include the North Delta and Eastside subregions. Trend detection can be improved through well-planned placement of high-frequency in-situ sensors (Bergamaschi et al. 2016, Jabusch et al. 2016). Because sensors do not capture all the variables of interest, a sensor network and a discrete sampling program should be planned to complement each other The previous reports provide specific recommendations for the placement of additional stations. These recommendations are synthesized in Figure 65.
ST2	What is the current status of the Delta ecosystem as influenced by nutrients?		A number of research studies have been completed, however, this question cannot be comprehensively addressed without agreement on the problem and all the factors contributing to the problem. The development of the Delta Nutrient Research Plan is expected to better define the issues.
ST2A	What is the current ecosystem status of habitat types in different types of Delta waterways, and how are the conditions related to nutrients?		See response ST2.
Sources, Pathways, Loadings & Processes (SPLP)			
SPLP1	Which sources, pathways, and processes contribute most to observed levels of nutrients?		The types and magnitudes of the most important sources, pathways, and processes are reasonably well understood. Novick et al. (2015) describe the Delta as a "giant biogeochemical reactor" where large scale transformations of nutrients entering the system occur. Nitrogen uptake by phytoplankton may be a dominant process in the system, although a full mass balance to test this theory still needs to be developed. The mechanistic, water quality-hydrodynamic models being developed for the Delta may be able to address the remaining questions in the future. However, the important processes, time-scales, and spatial scales need to be better defined in order to know the best way forward.

	Nutrient Assessment Questions	Current Knowledge	Summary
SPLP1A	How have nutrient or nutrient-related source controls and water management actions changed ambient levels of nutrients and nutrient-associated parameters?		Data analysis work done by USGS, ASC, and other groups have demonstrated relationships between certain significant actions (e.g., improvements of wastewater treatment) and trends in nutrient loads and concentrations. There are gaps in our knowledge because monitoring data are not always available in the right place and the right time to measure the effects of management actions.
SPLP1B	What are the loads from tributaries to the Delta?		USGS monitoring at Freeport and Vernalis provides data on loads to the Delta from the major tributaries, with the exception of short-term high intensity events. Less is known about loads from other tributaries such as the Yolo Bypass or Eastside tributaries. USGS is starting to fill some of these gaps with a nitrate sensor network in the North Delta.
SPLP1C	What are the sources and loads of nutrients within the Delta?		Good information exists on point source loadings within the Delta, but non-point source loads and sinks are not well understood. Special studies to quantify internal sources and process rates will be needed to parameterize a model to answer this question fully.
SPLP1D	What role do internal sources play in influencing observed nutrient levels?		See SPLP1C
SPLP1E	Which factors in the Delta influence the effects of nutrients?		These factors are not well understood. The Delta Nutrient Research Plan white papers are providing an overview on the state of knowledge with regards to the effects of nutrients on the abundance and distribution of blue green algae and macrophytes, and the effects of nutrient forms and ratios on algal species composition. A validated mechanistic model will be the right tool to answer these questions. However, the important processes, time-scales, and spatial scales need to be better defined in order to know the best way forward.
SPLP1F	What are the types and sources of nutrient sinks within the Delta?		See SPLP1C
SPLP1G	What are the types and magnitudes of nutrient exports from the Delta to Suisun Bay and water intakes for the State and Federal Water Projects?		Novick et al. (2015) provides estimates of the types and magnitudes of nutrient loads from the Delta to the water intakes of the State and Federal water projects.

	Nutrient Assessment Questions	Current Knowledge	Summary
Forecasting Scenarios (FS)			
FS1	How will ambient water quality conditions respond to potential or planned future source control actions, restoration projects, and water resource management changes?		Addressing this question requires a validated mechanistic model which is currently under development but not ready for use. Any models developed should be employed in an adaptive management framework that includes targeted laboratory and field experiments designed to test the effects of management actions, and to elucidate model mechanisms and parameterization.

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6 Figures

All report figures are included on the following pages.

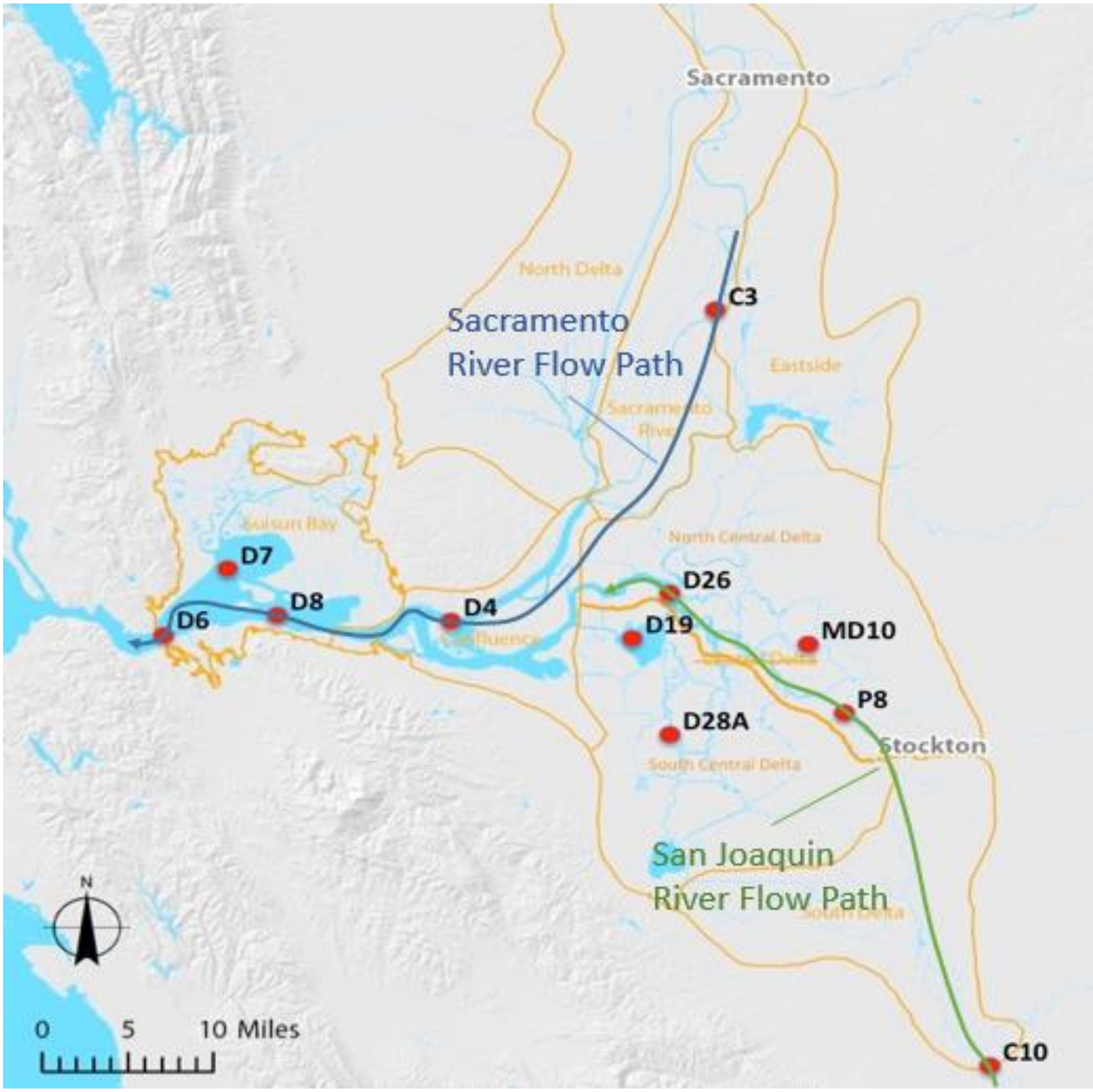

Figure 1. DWR-EMP discrete water quality monitoring stations, in relationship to proposed subregions (Jabusch et al. 2016). The general flow-paths of the Sacramento and San Joaquin Rivers are also shown.

These locations have been sampled since 1975. This synthesis report evaluates data collected at these stations over a recent 16-year period, from October 2001 to September 2016.

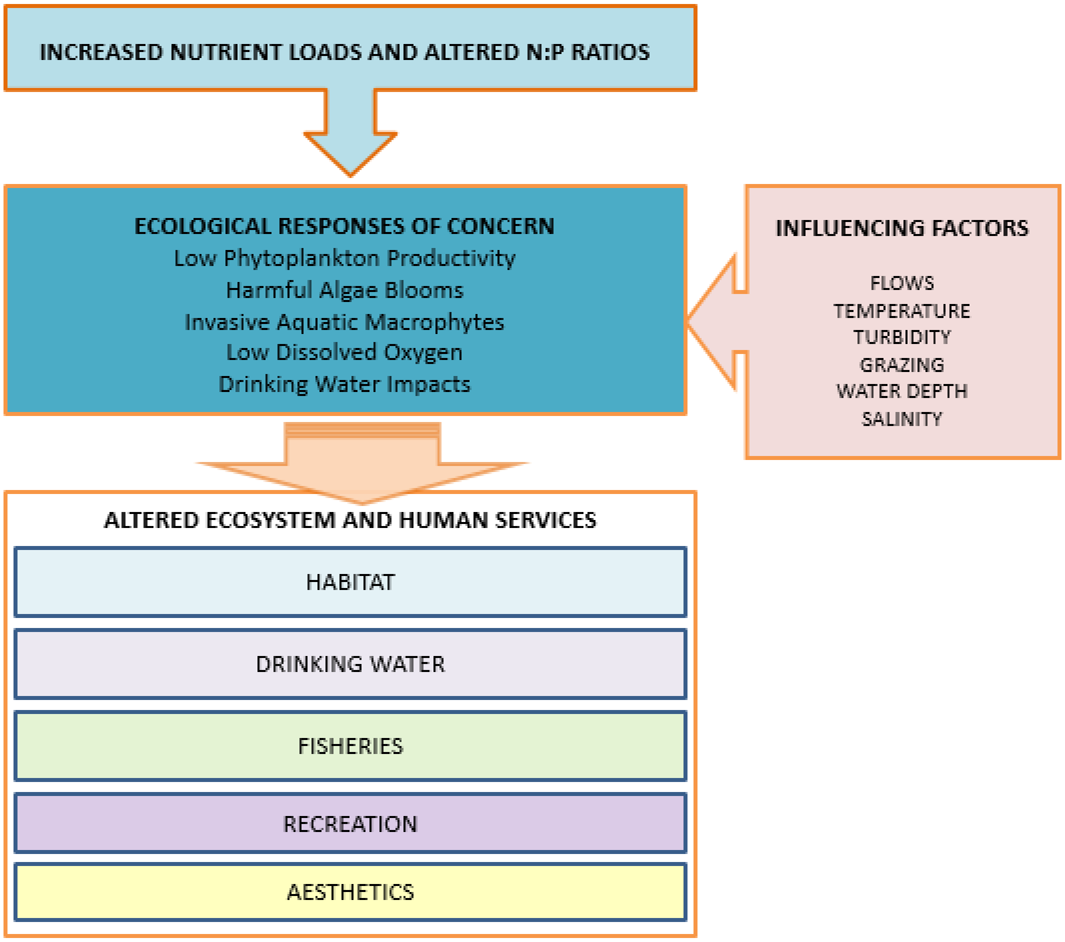

Figure 2. Simplified conceptual framework showing the linkage of nutrients loading, ecological response, influencing factors modulating the ecological response, and altered ecological and human services.

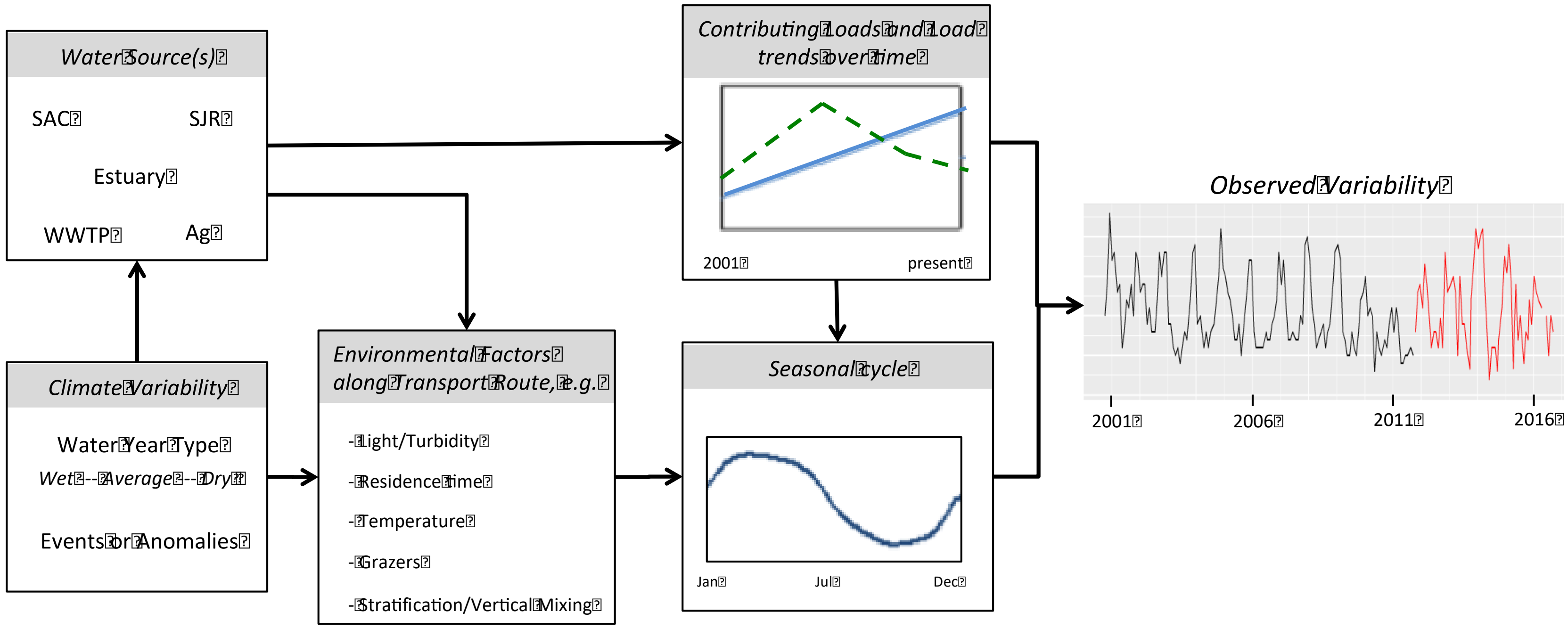

Figure 3. Conceptual model for nutrient variability in the Sacramento-San Joaquin Delta.

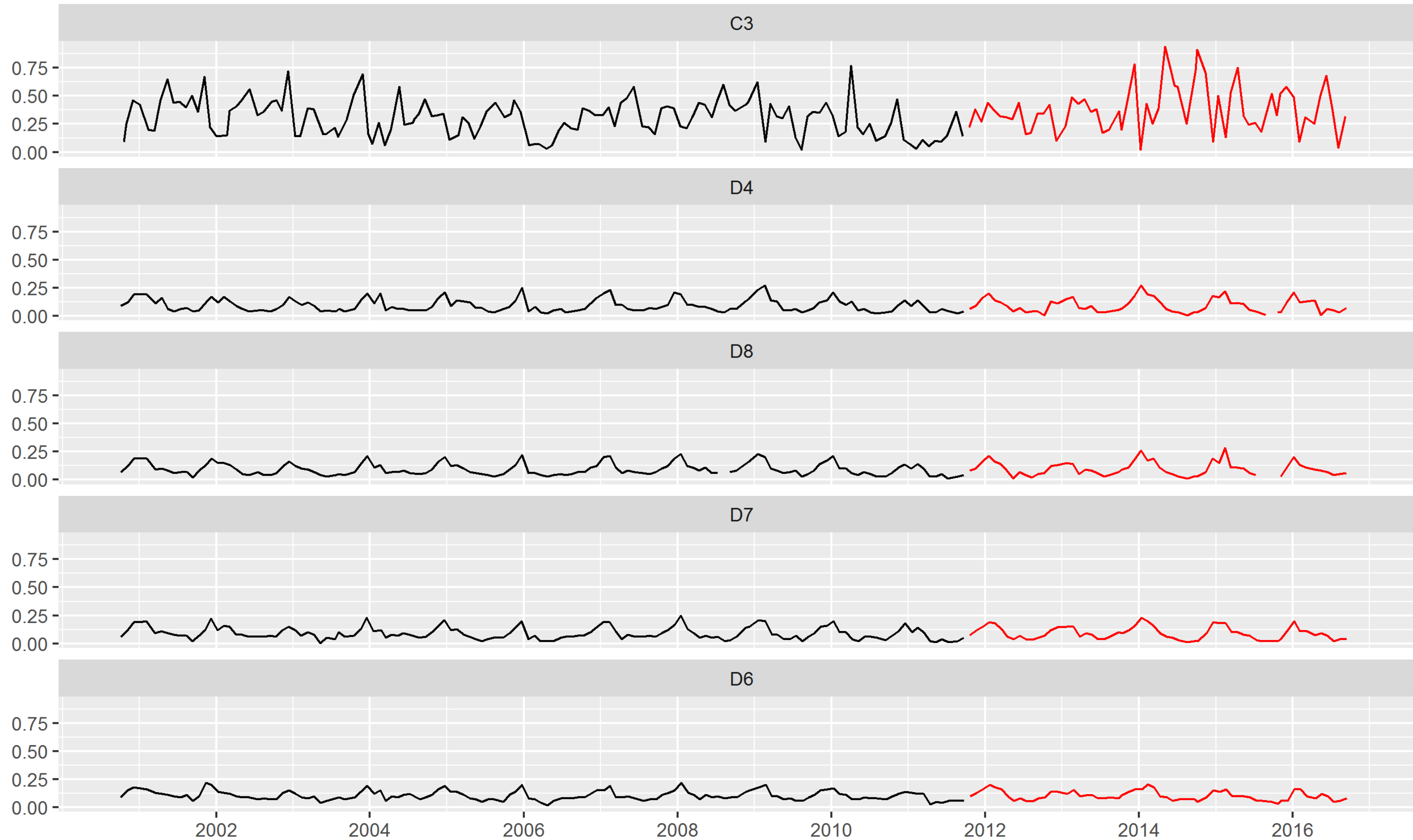

Figure 4. Time-series of NH_4 (mg N/L) at DWR-EMP water quality monitoring stations in the Sacramento River (C3), Confluence (D4), and Suisun Bay (D8, D7, D6), WY2001–2016.

C3 (Sacramento River at Hood) is the site farthest upstream on the Sacramento River, D6 (Martinez) is the site farthest down-estuary in Suisun Bay. Highlighted in red: most recent data from drought years (WY 2012–2016).

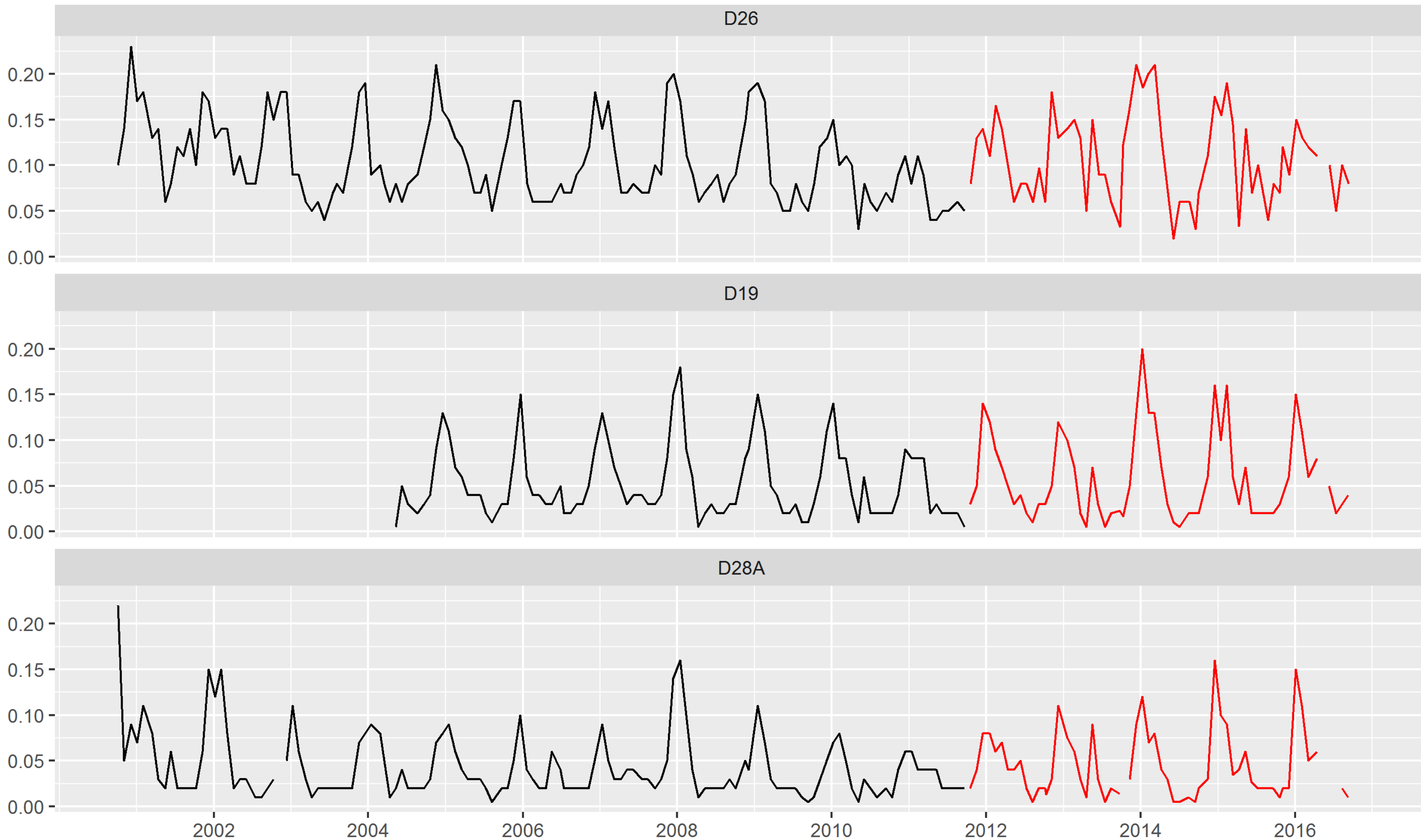

Figure 5. Time-series of NH_4 (mg N/L) at DWR-EMP water quality monitoring stations in the Central Delta, WY2001–2016.

The sites in this panel are on the flowpath of Sacramento River water towards the water pumps in the south Delta: D26 (San Joaquin River at Potato Point, North Central Delta), D19 (Frank's Tract, South Central Delta), D28 (Old River, South Central Delta). Highlighted in red: most recent data from drought years (WY 2012–2016).

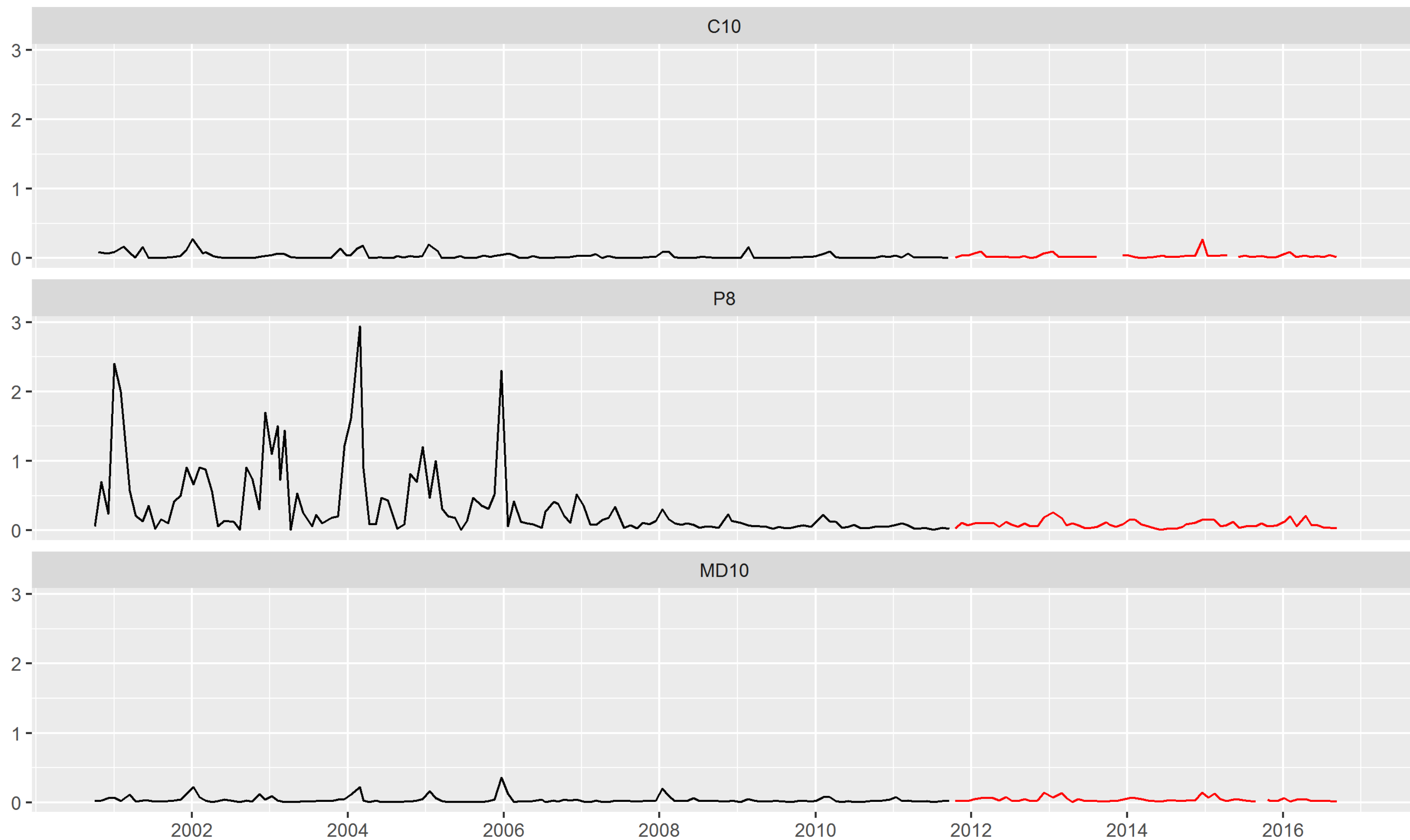

Figure 6. Time-series of NH_4 (mg N/L) at DWR-EMP water quality monitoring stations in the South Delta and North Central Delta, WY2001–2016.

The sites in this panel are along the flowpath of the San Joaquin River: C10 (San Joaquin River at Vernalis), P8 (San Joaquin River at Buckley Cove), and MD10 (Disappointment Slough). Highlighted in red: most recent data from drought years (WY 2012–2016).

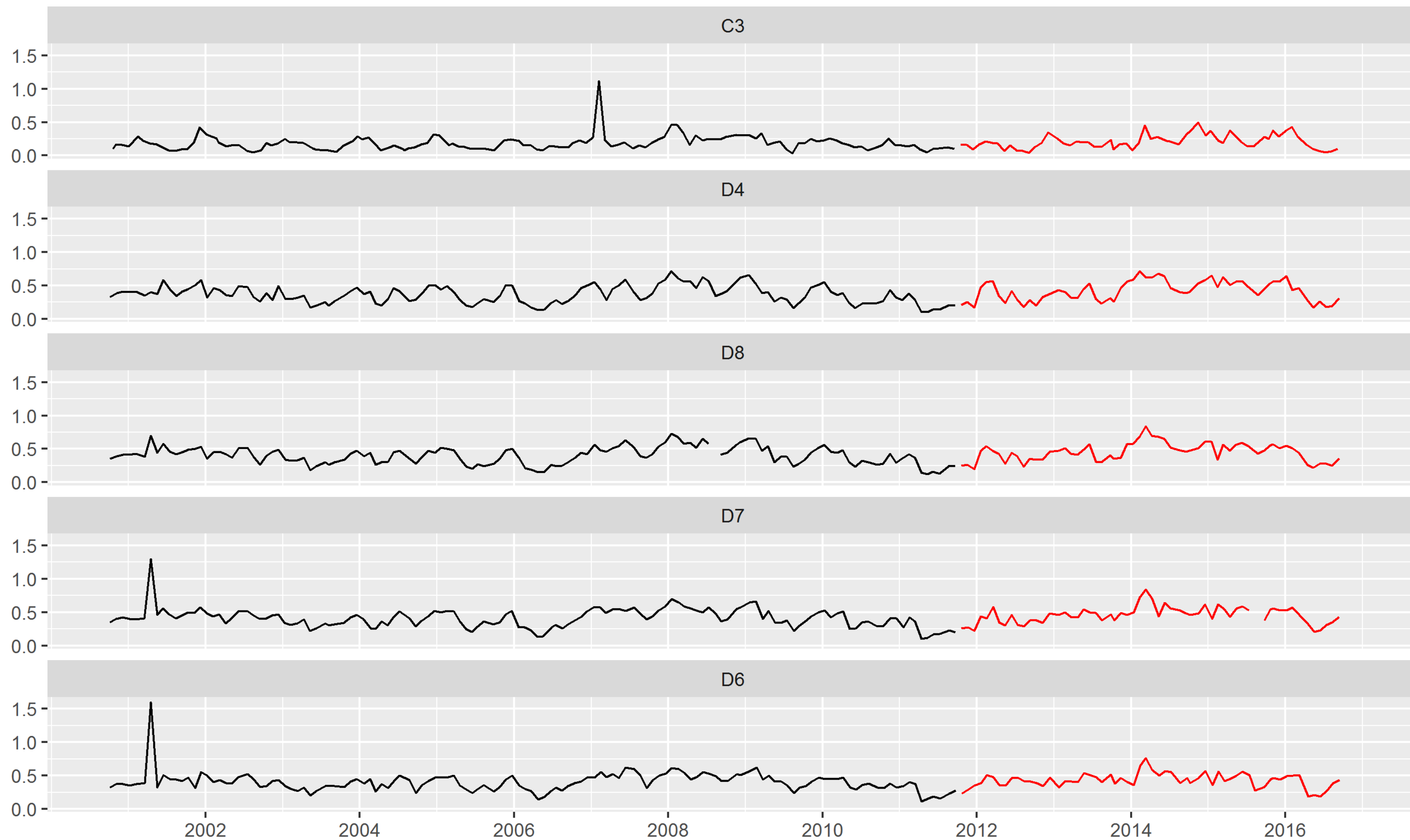

Figure 7. Time-series of NO_3 (mg N/L) at DWR-EMP water quality monitoring stations in the Sacramento River (C3), Confluence (D4), and Suisun Bay (D8, D7, D6), WY2001–2016.

C3 (Sacramento River at Hood) is the site farthest upstream on the Sacramento River, D6 (Martinez) is the site farthest down-estuary in Suisun Bay. Highlighted in red: most recent data from drought years (WY 2012–2016).

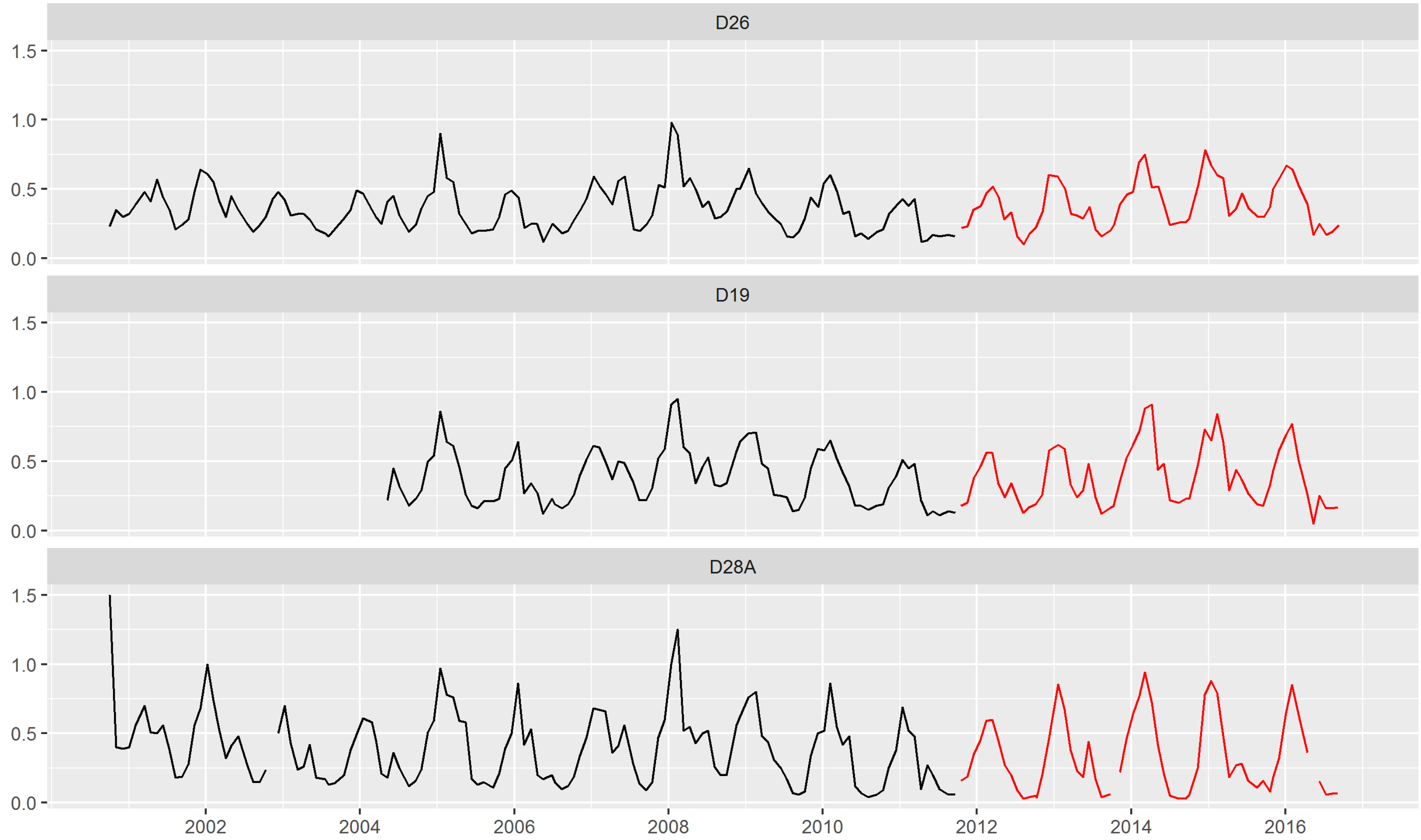

Figure 8. Time-series of NO_3 (mg N/L) at DWR-EMP water quality monitoring stations in the Central Delta, WY2001–2016.

The sites in this panel are on the flowpath of Sacramento River water towards the water pumps in the south Delta: D26 (San Joaquin River at Potato Point) D19 (Frank's Tract), D28 (Old River). Highlighted in red: most recent data from drought years (WY 2012–2016).

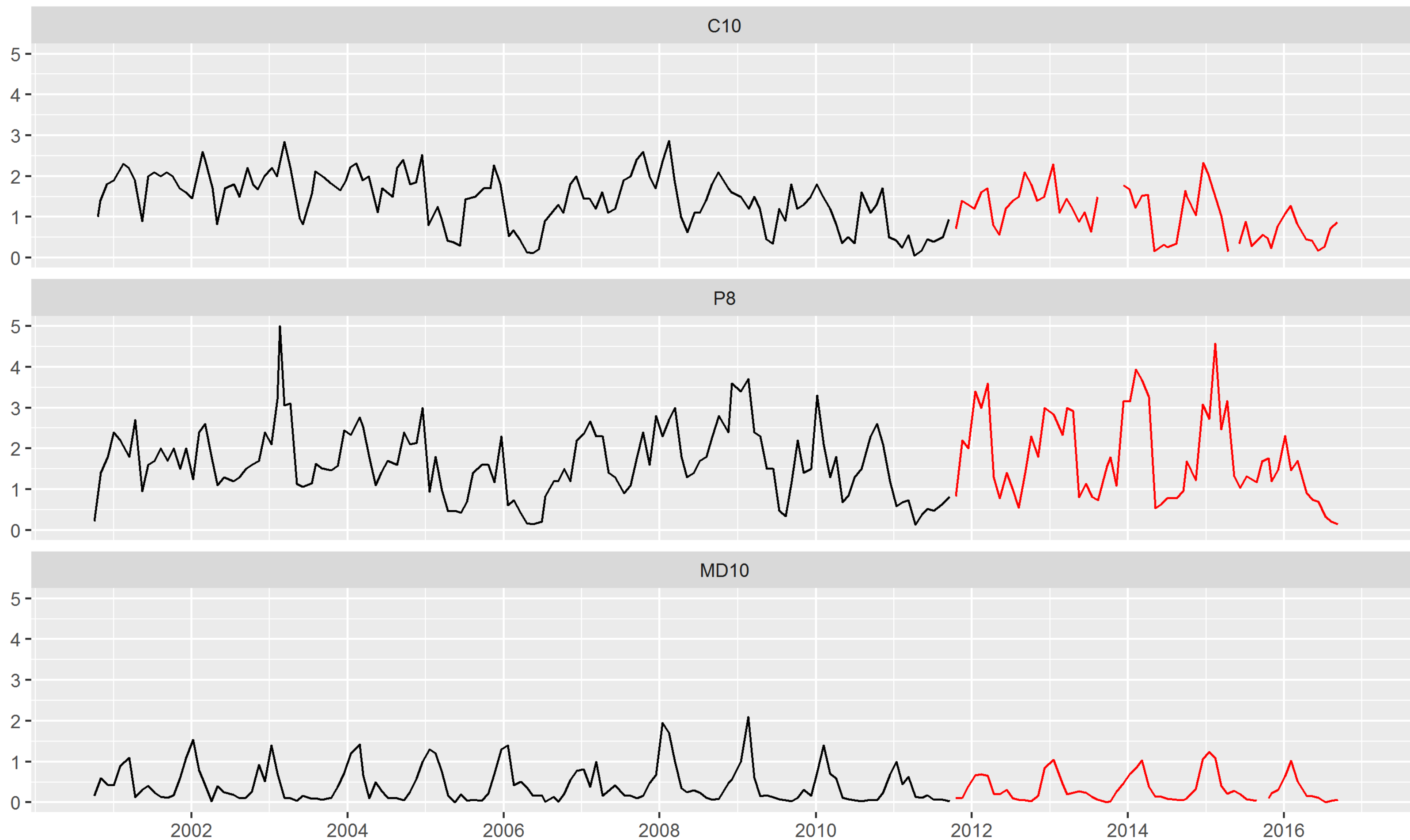

Figure 9. Time-series of NO_3 (mg N/L) at DWR-EMP water quality monitoring stations in the South Delta and North Central Delta, WY2001–2016.

The sites in this panel are along the flowpath of the San Joaquin River: C10 (San Joaquin River at Vernalis), P8 (San Joaquin River at Buckley Cove), and MD10 (Disappointment Slough). Highlighted in red: most recent data from drought years (WY 2012–2016).

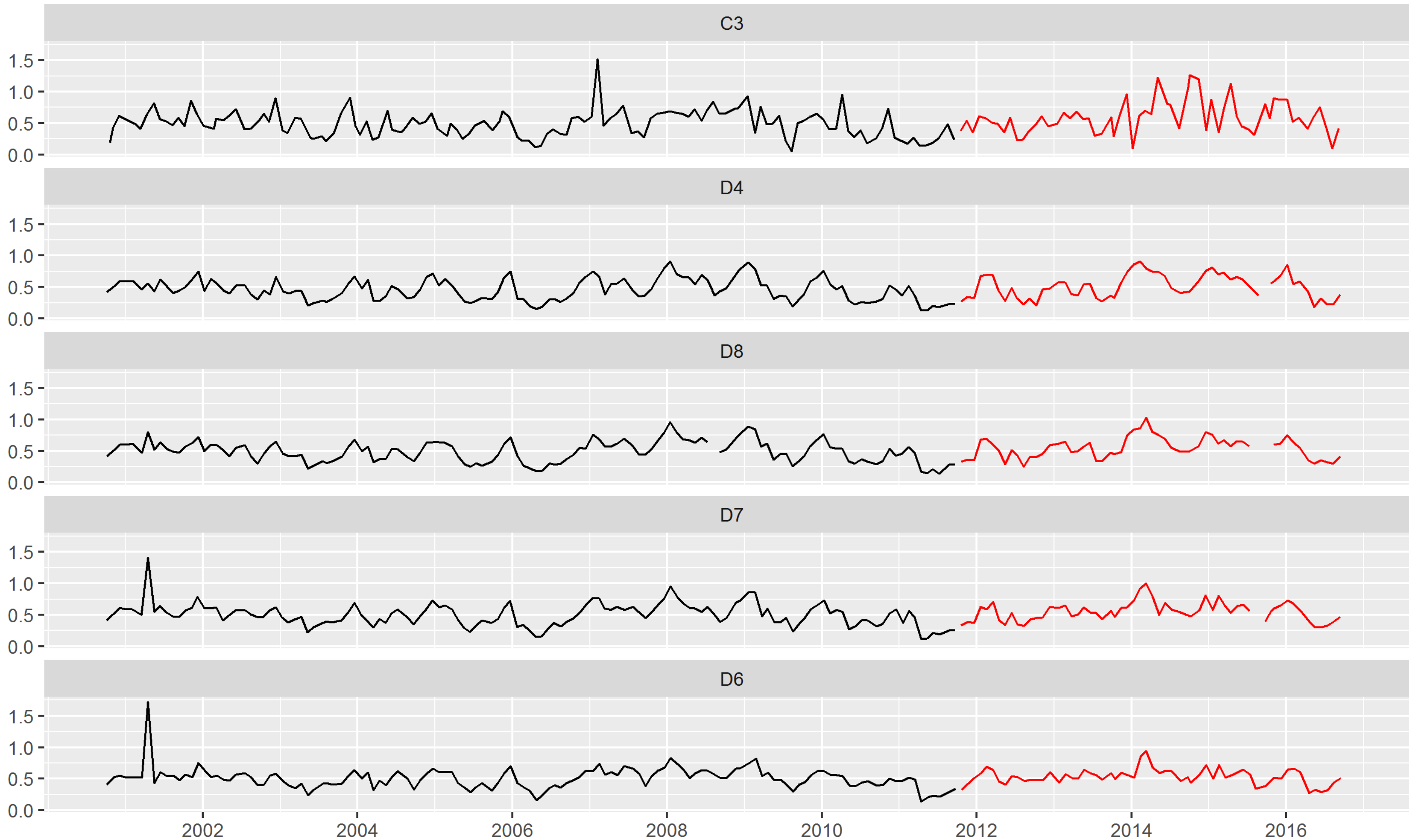

Figure 10. Time-series of DIN (mg N/L) at DWR-EMP water quality monitoring stations in the Sacramento River (C3), Confluence (D4), and Suisun Bay (D8, D7, D6), WY2001–2016.

C3 (Sacramento River at Hood) is the site farthest upstream on the Sacramento River, D6 (Martinez) is the site farthest down-estuary in Suisun Bay. Highlighted in red: most recent data from drought years (WY 2012–2016).

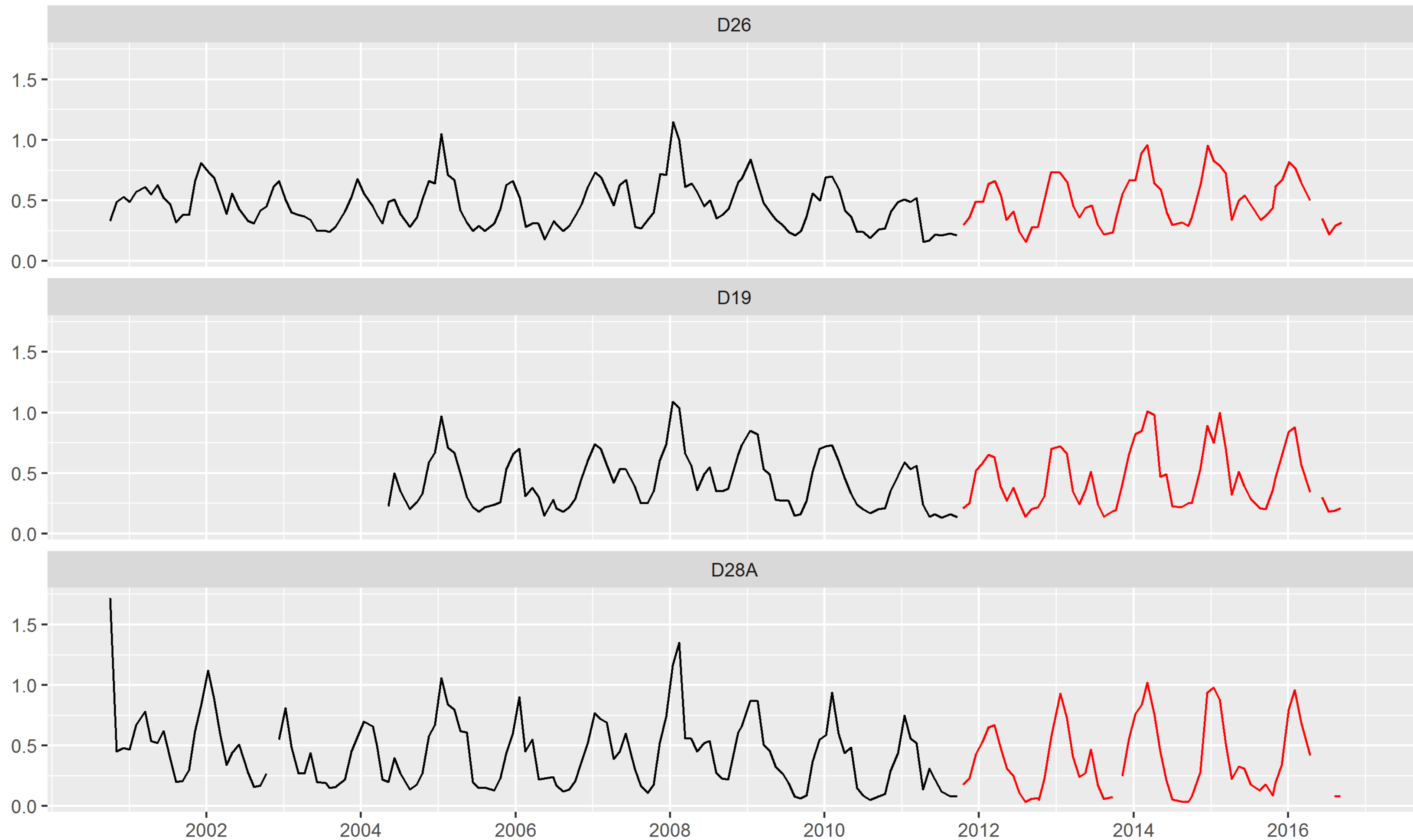

Figure 11. Time-series of DIN (mg N/L) at DWR-EMP water quality monitoring stations in the Central Delta, WY2001–2016.

The sites in this panel are on the flowpath of Sacramento River water towards the water pumps in the south Delta: D26 (San Joaquin River at Potato Point) D19 (Frank's Tract), D28 (Old River). Highlighted in red: most recent data from drought years (WY 2012–2016).

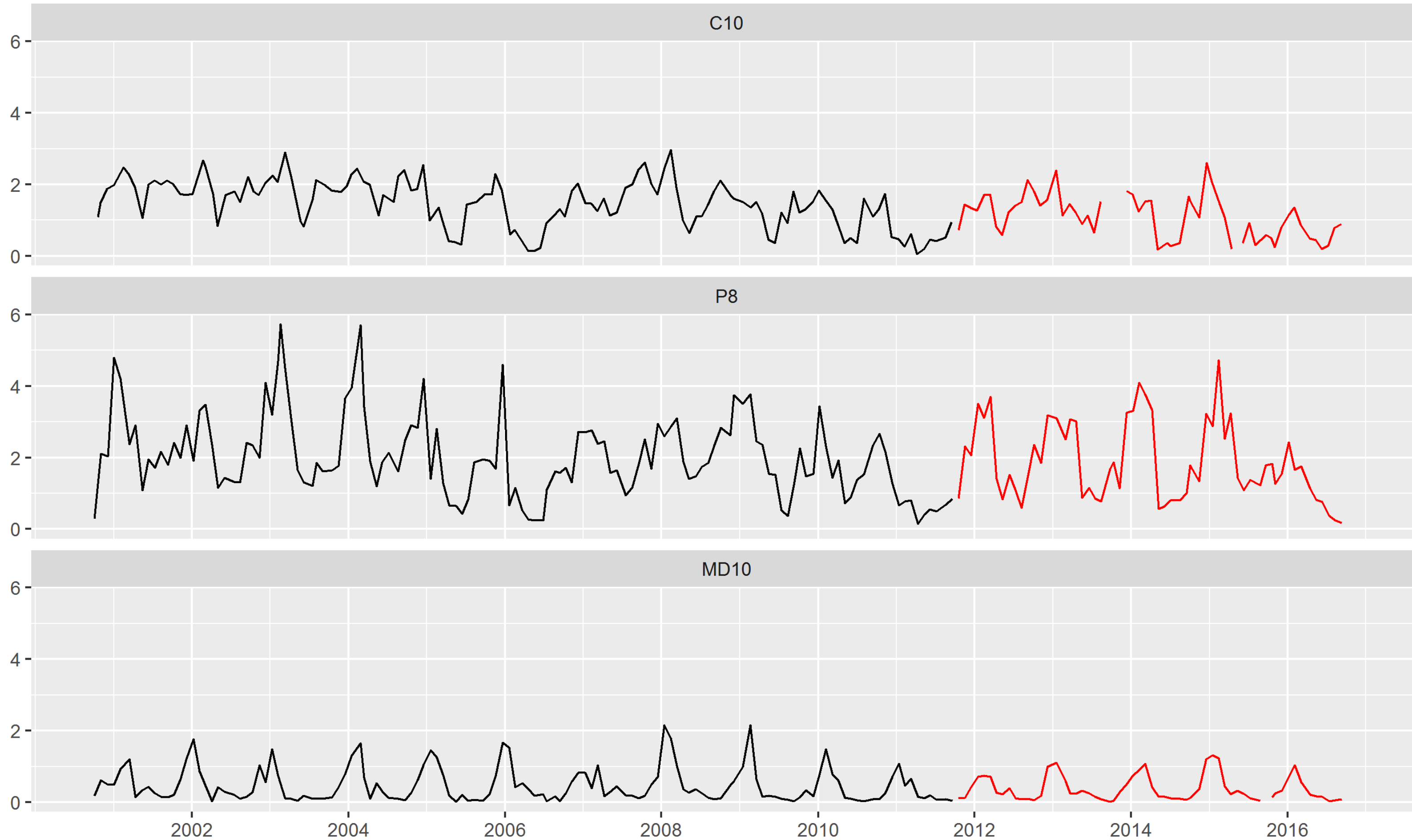

Figure 12. Time-series of DIN (mg N/L) at DWR-EMP water quality monitoring stations in the South Delta and North Central Delta, WY2001–2016.

The sites in this panel are along the flowpath of the San Joaquin River: C10 (San Joaquin River at Vernalis), P8 (San Joaquin River at Buckley Cove), and MD10 (Disappointment Slough). Highlighted in red: most recent data from drought years (WY 2012–2016).

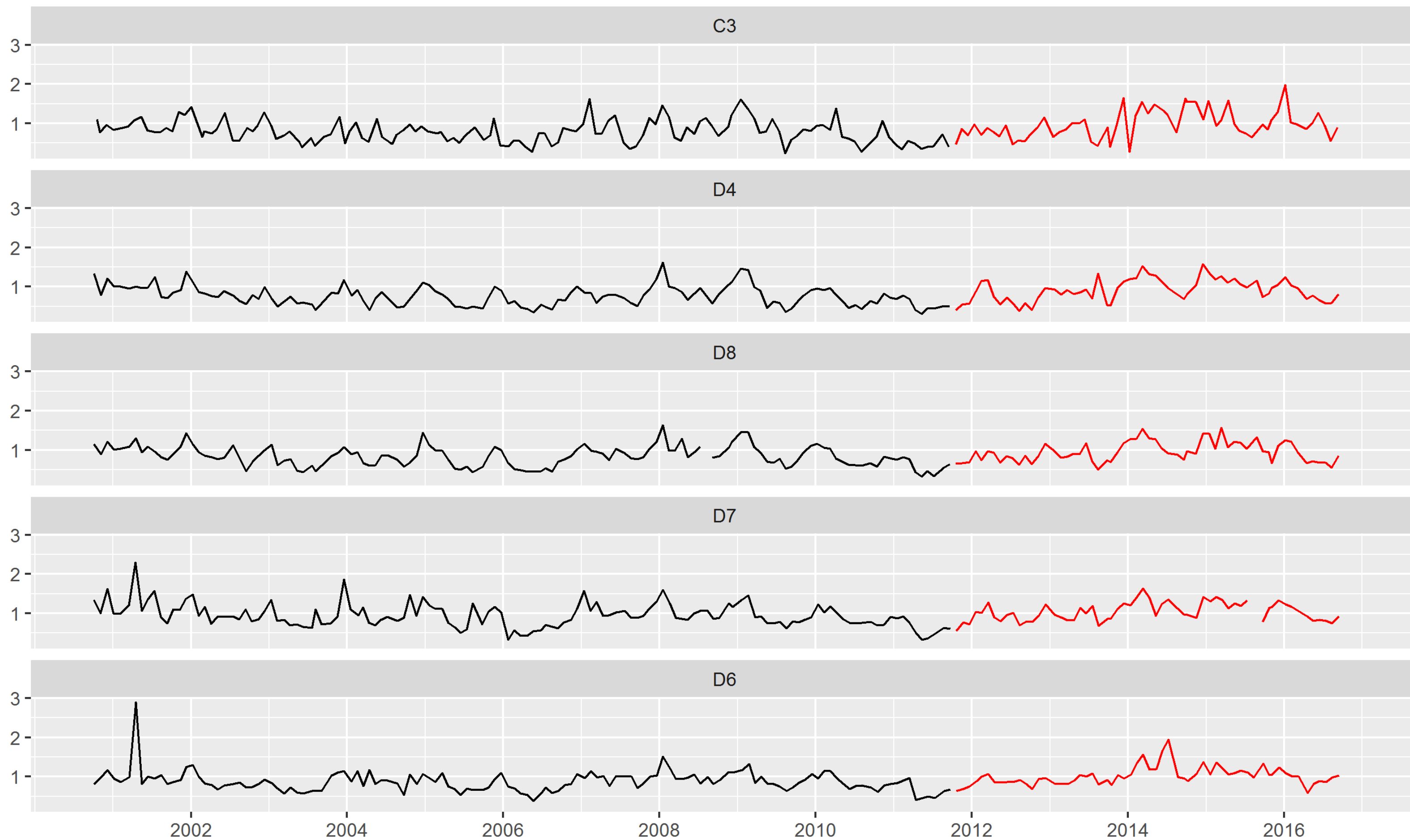

Figure 13. Time-series of TN (mg N/L) at DWR-EMP water quality monitoring stations in the Sacramento River (C3), Confluence (D4), and Suisun Bay (D8, D7, D6), WY2001–2016.

C3 (Sacramento River at Hood) is the site farthest upstream on the Sacramento River, D6 (Martinez) is the site farthest down-estuary in Suisun Bay. Highlighted in red: most recent data from drought years (WY 2012–2016).

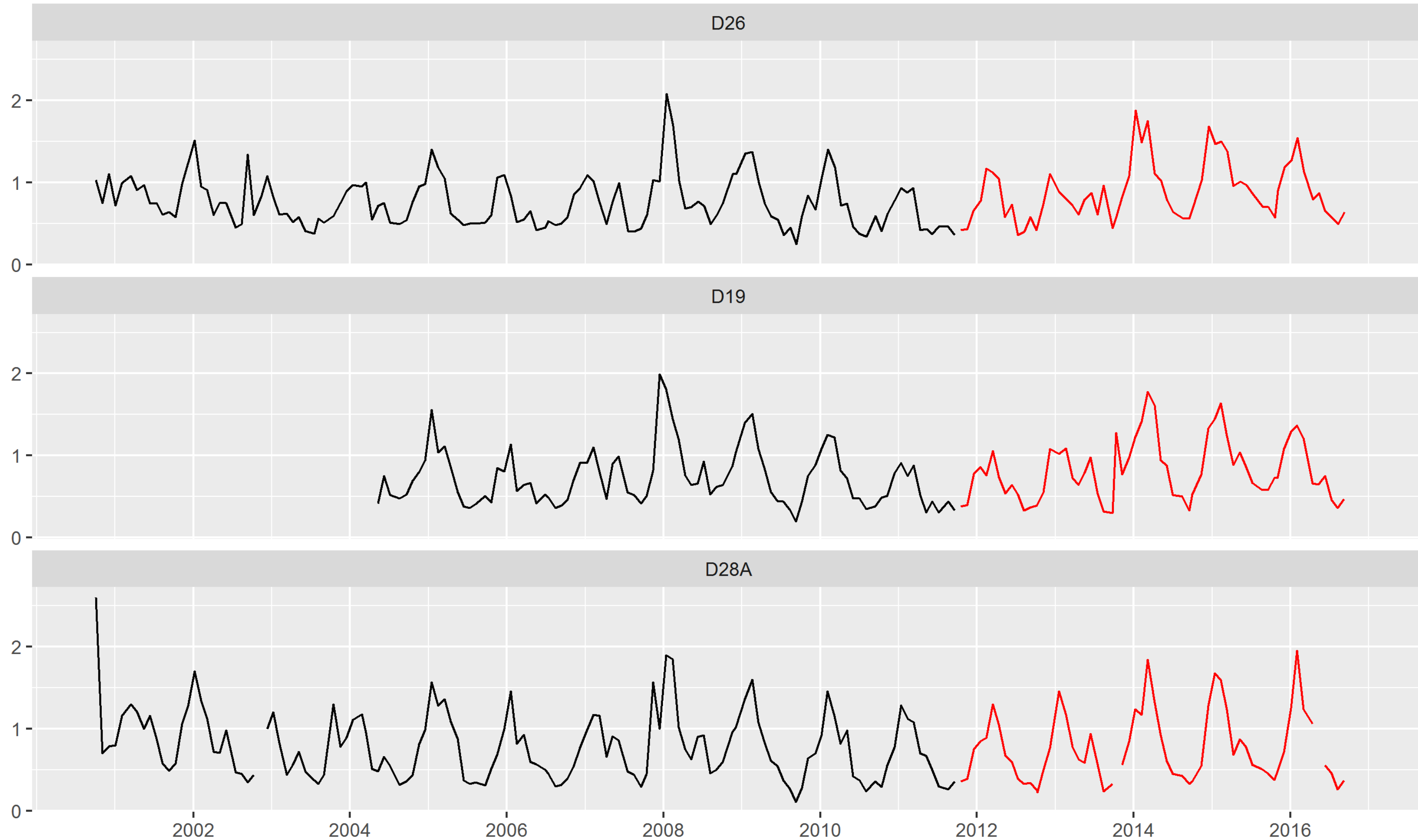

Figure 14. Time-series of TN (mg N/L) at DWR-EMP water quality monitoring stations in the Central Delta, WY2001–2016.

The sites in this panel are on the flowpath of Sacramento River water towards the water pumps in the south Delta: D26 (San Joaquin River at Potato Point) D19 (Frank's Tract), D28 (Old River). Highlighted in red: most recent data from drought years (WY 2012–2016).

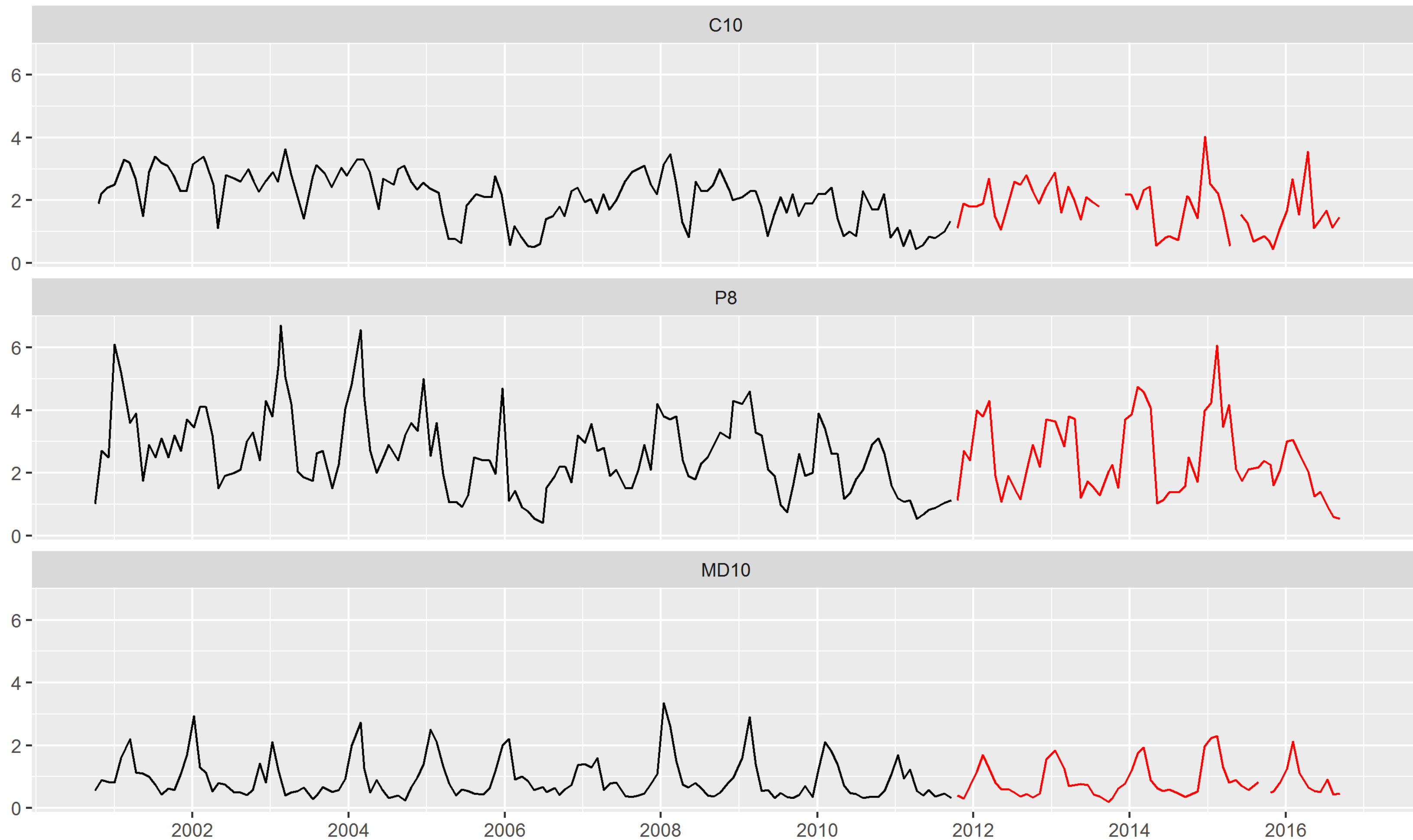

Figure 15. Time-series of TN (mg N/L) at DWR-EMP water quality monitoring stations in the South Delta and North Central Delta, WY2001–2016.

The sites in this panel are along the flowpath of the San Joaquin River: C10 (San Joaquin River at Vernalis), P8 (San Joaquin River at Buckley Cove), and MD10 (Disappointment Slough). Highlighted in red: most recent data from drought years (WY 2012–2016).

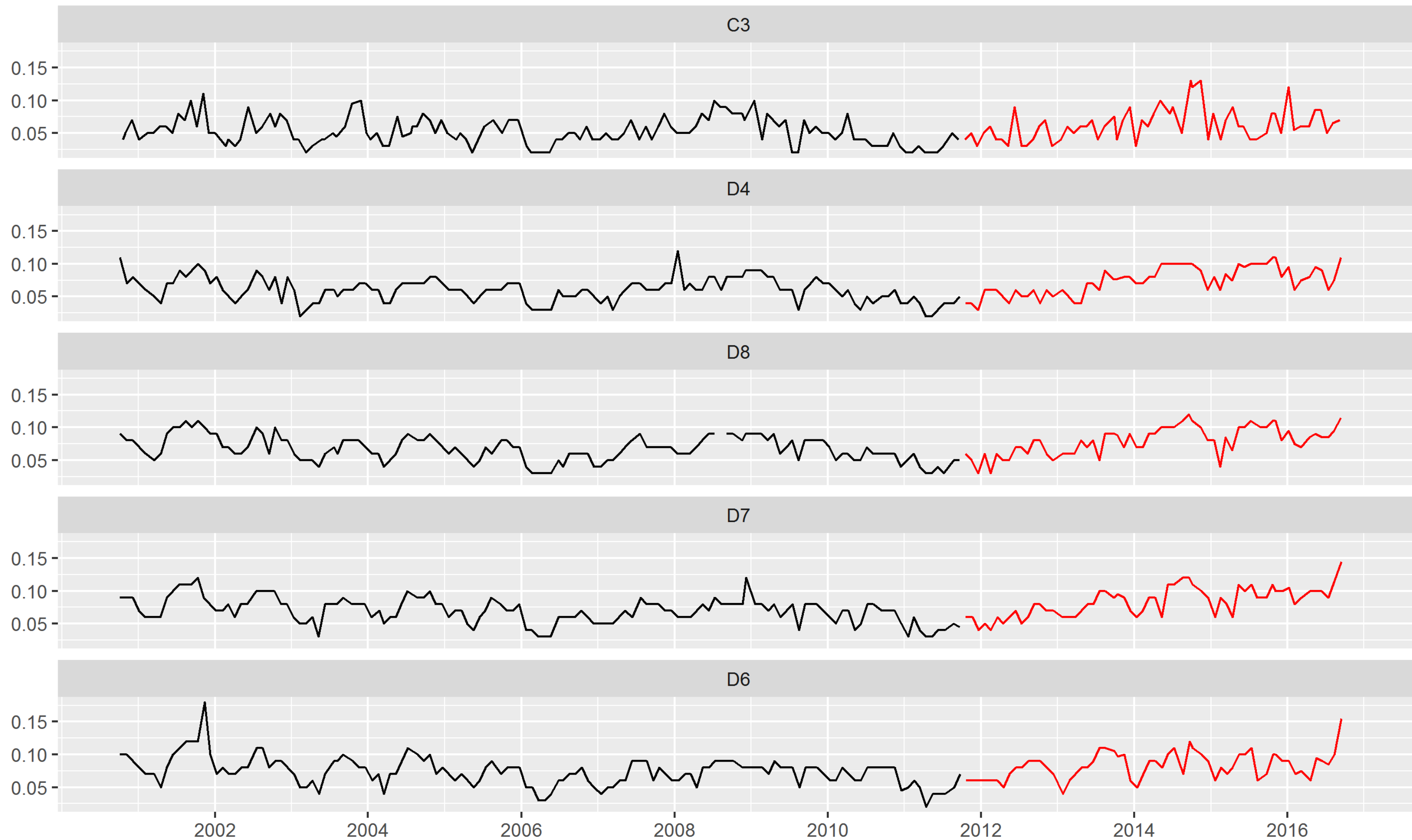

Figure 16. Time-series of PO_4 (mg P/L) at DWR-EMP water quality monitoring stations in the Sacramento River (C3), Confluence (D4), and Suisun Bay (D8, D7, D6), WY2001–2016.

C3 (Sacramento River at Hood) is the site farthest upstream on the Sacramento River, D6 (Martinez) is the site farthest down-estuary in Suisun Bay. Highlighted in red: most recent data from drought years (WY 2012–2016).

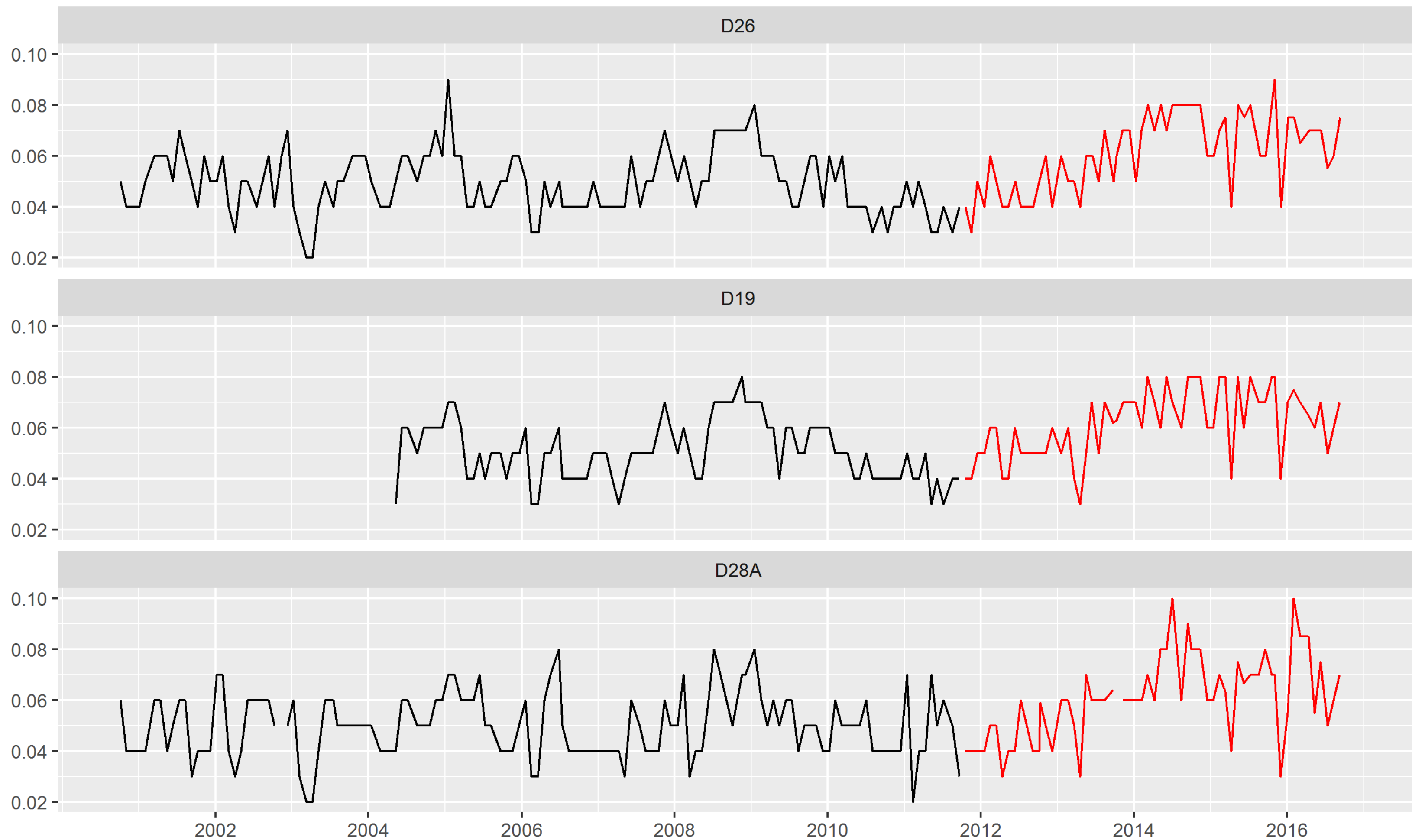

Figure 17. Time-series of PO_4 (mg P/L) at DWR-EMP water quality monitoring stations in the Central Delta, WY2001–2016.

The sites in this panel are on the flowpath of Sacramento River water towards the water pumps in the south Delta: D26 (San Joaquin River at Potato Point) D19 (Frank's Tract), D28 (Old River). Highlighted in red: most recent data from drought years (WY 2012–2016).

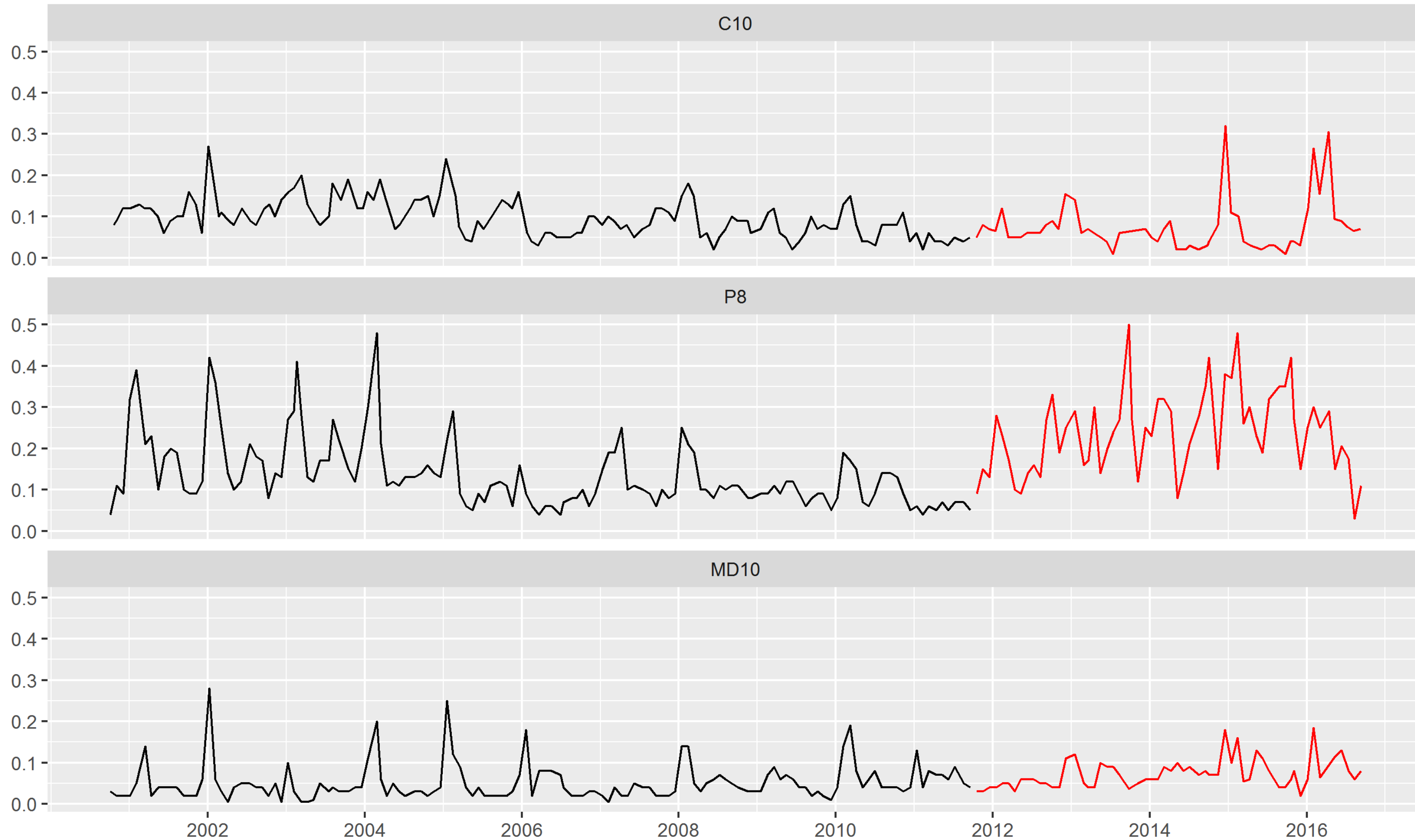

Figure 18. Time-series of PO_4 (mg P/L) at DWR-EMP water quality monitoring stations in the South Delta and North Central Delta, WY2001–2016.

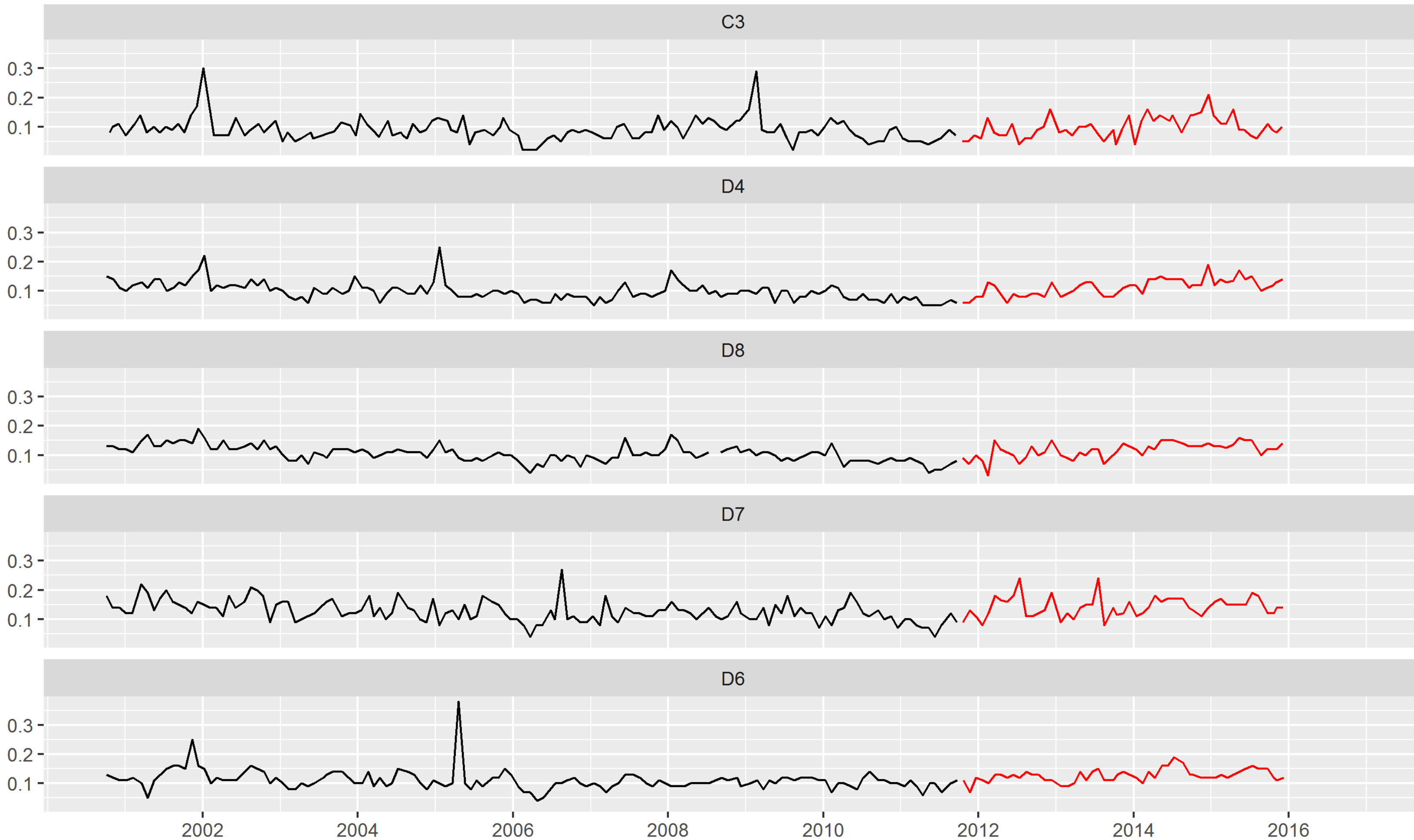

Figure 19. Time-series of TP (mg P/L) at DWR-EMP water quality monitoring stations in the Sacramento River (C3), Confluence (D4), and Suisun Bay (D8, D7, D6), WY2001–2016.

C3 (Sacramento River at Hood) is the site farthest upstream on the Sacramento River, D6 (Martinez) is the site farthest down-estuary in Suisun Bay. Highlighted in red: most recent data from drought years (WY 2012–2016).

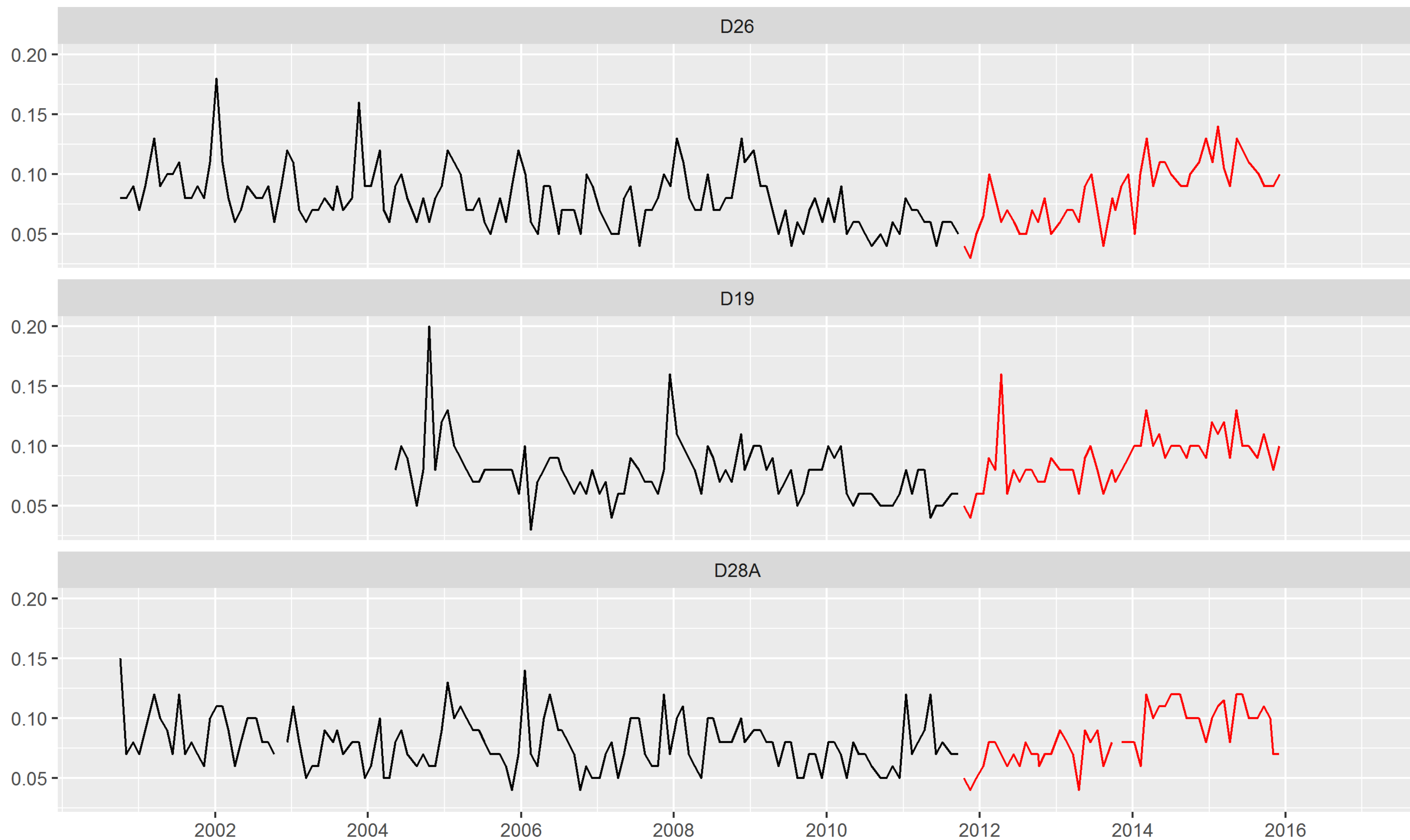

Figure 20. Time-series of TP (mg P/L) at DWR-EMP water quality monitoring stations in the Central Delta, WY2001–2016.

The sites in this panel are on the flowpath of Sacramento River water towards the water pumps in the south Delta: D26 (San Joaquin River at Potato Point) D19 (Frank's Tract), D28 (Old River). Highlighted in red: most recent data from drought years (WY 2012–2016).

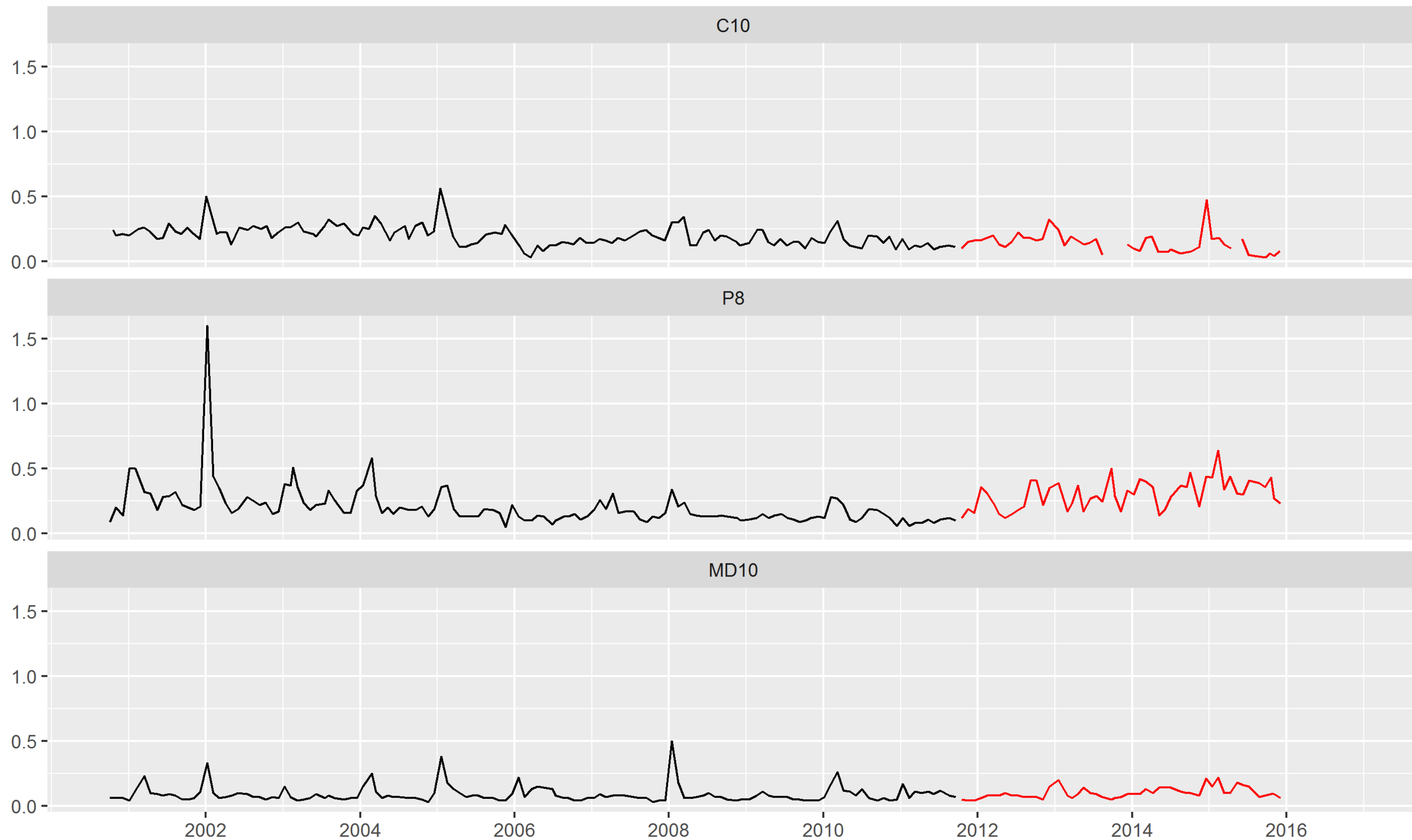

Figure 21. Time-series of TP (mg P/L) at DWR-EMP water quality monitoring stations in the South Delta and North Central Delta, WY2001–2016.

The sites in this panel are along the flowpath of the San Joaquin River: C10 (San Joaquin River at Vernalis), P8 (San Joaquin River at Buckley Cove), and MD10 (Disappointment Slough). Highlighted in red: most recent data from drought years (WY 2012–2016).

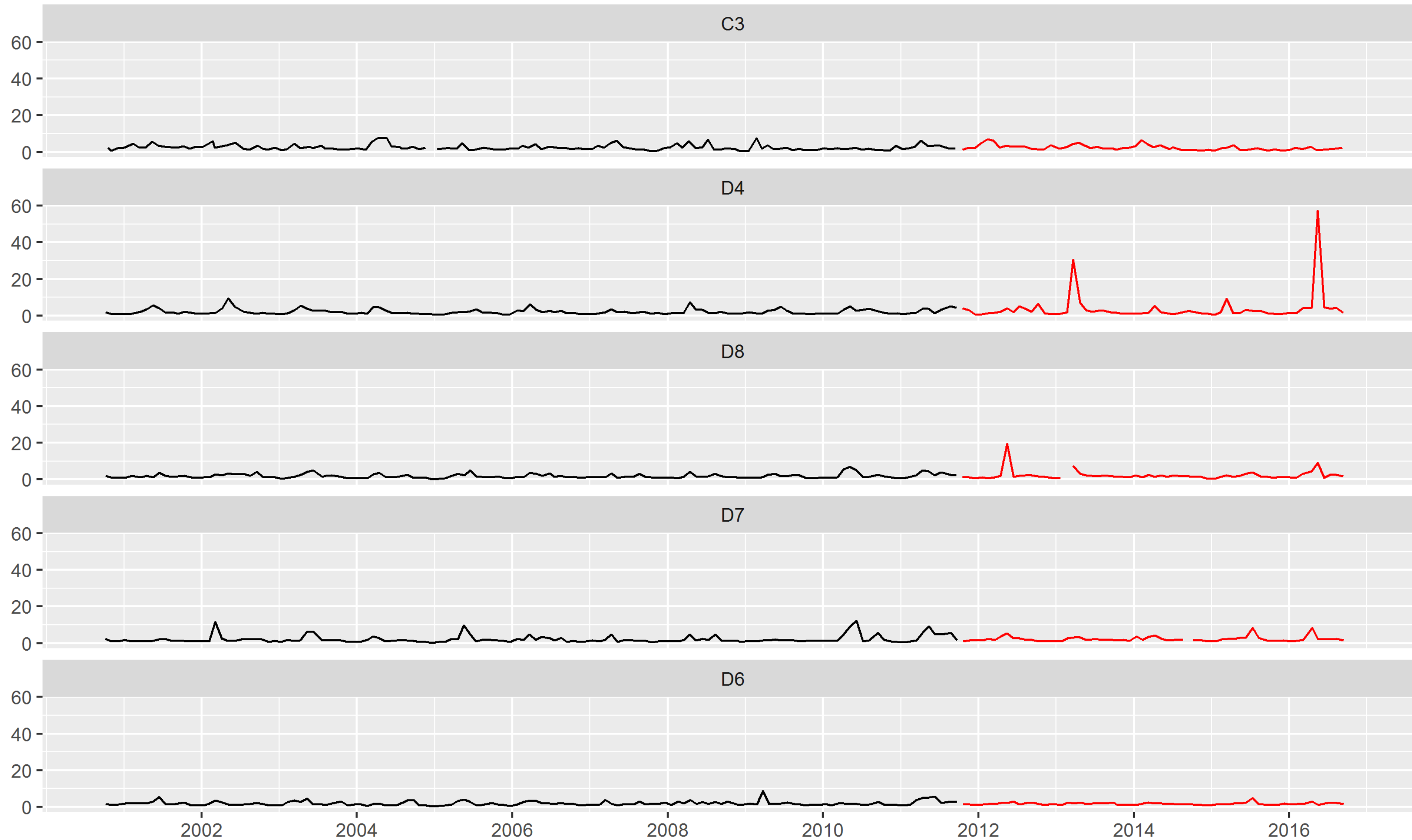

Figure 22. Time-series of Chl-a (µg /L) at DWR-EMP water quality monitoring stations in the Sacramento River (C3), Confluence (D4), and Suisun Bay (D8, D7, D6), WY2001–2016.

C3 (Sacramento River at Hood) is the site farthest upstream on the Sacramento River, D6 (Martinez) is the site farthest down-estuary in Suisun Bay. Highlighted in red: most recent data from drought years (WY 2012–2016).

Figure 23. Time-series of Chl-a (µg /L) at DWR-EMP water quality monitoring stations in the Central Delta, WY2001–2016.

The sites in this panel are on the flowpath of Sacramento River water towards the water pumps in the south Delta: D26 (San Joaquin River at Potato Point) D19 (Frank's Tract), D28 (Old River). Highlighted in red: most recent data from drought years (WY 2012–2016).

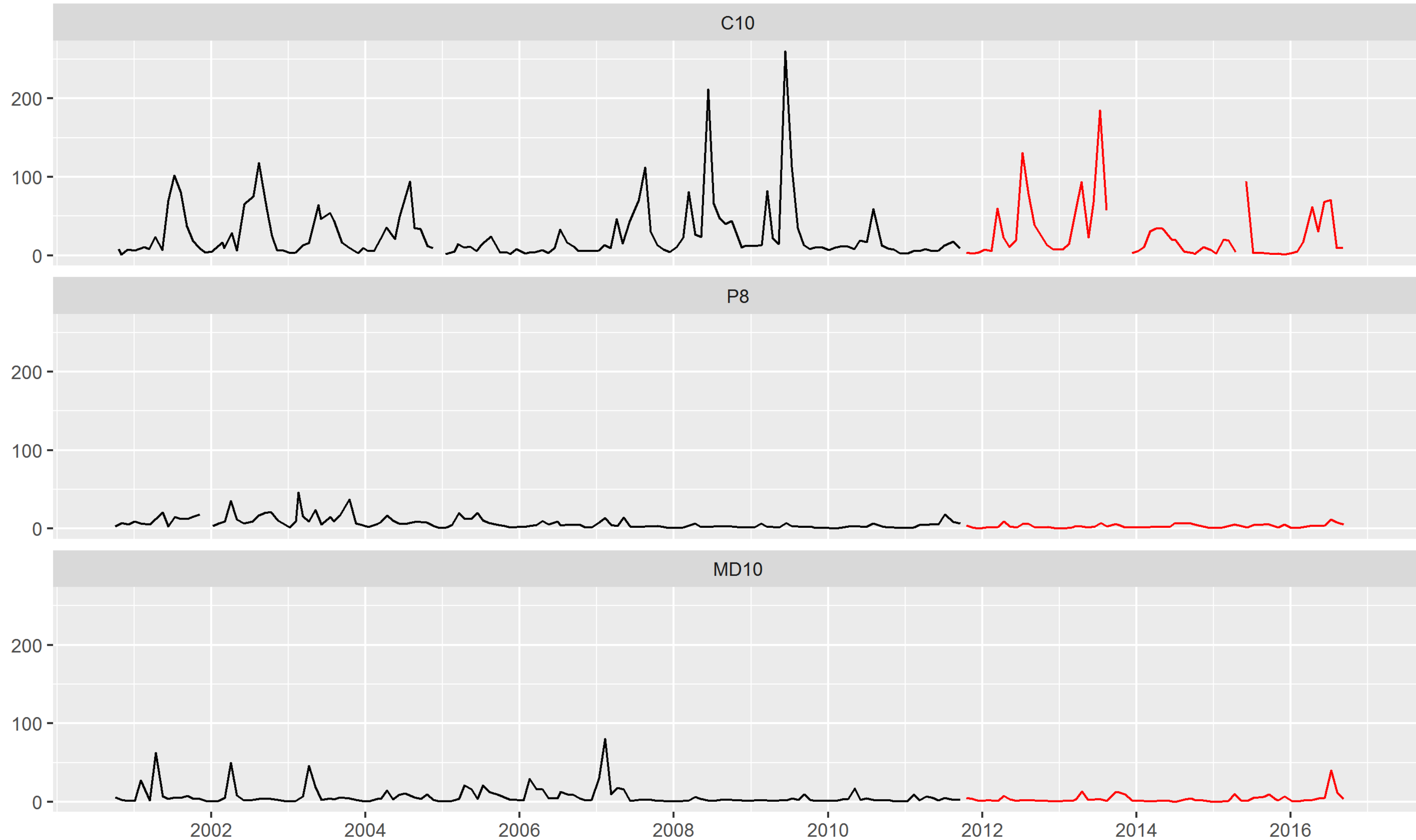

Figure 24. Time-series of Chl-a (µg /L) at DWR-EMP water quality monitoring stations in the South Delta and North Central Delta, WY2001–2016.

The sites in this panel are along the flowpath of the San Joaquin River: C10 (San Joaquin River at Vernalis), P8 (San Joaquin River at Buckley Cove), and MD10 (Disappointment Slough). Highlighted in red: most recent data from drought years (WY 2012–2016).

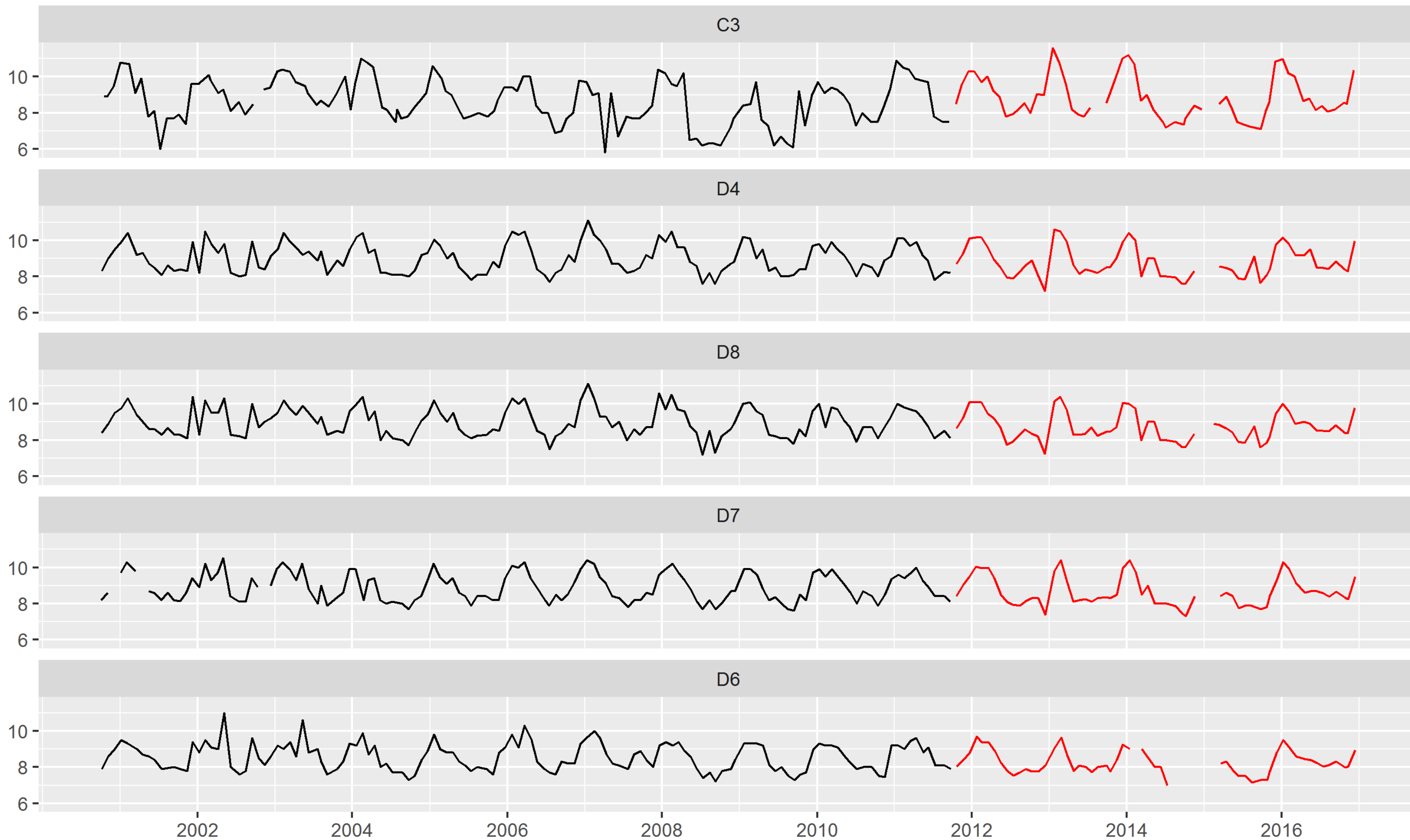

Figure 25. Time-series of DO (mg /L) at DWR-EMP water quality monitoring stations in the Sacramento River (C3), Confluence (D4), and Suisun Bay (D8, D7, D6), WY2001–2016.

C3 (Sacramento River at Hood) is the site farthest upstream on the Sacramento River, D6 (Martinez) is the site farthest down-estuary in Suisun Bay. Highlighted in red: most recent data from drought years (WY 2012–2016).

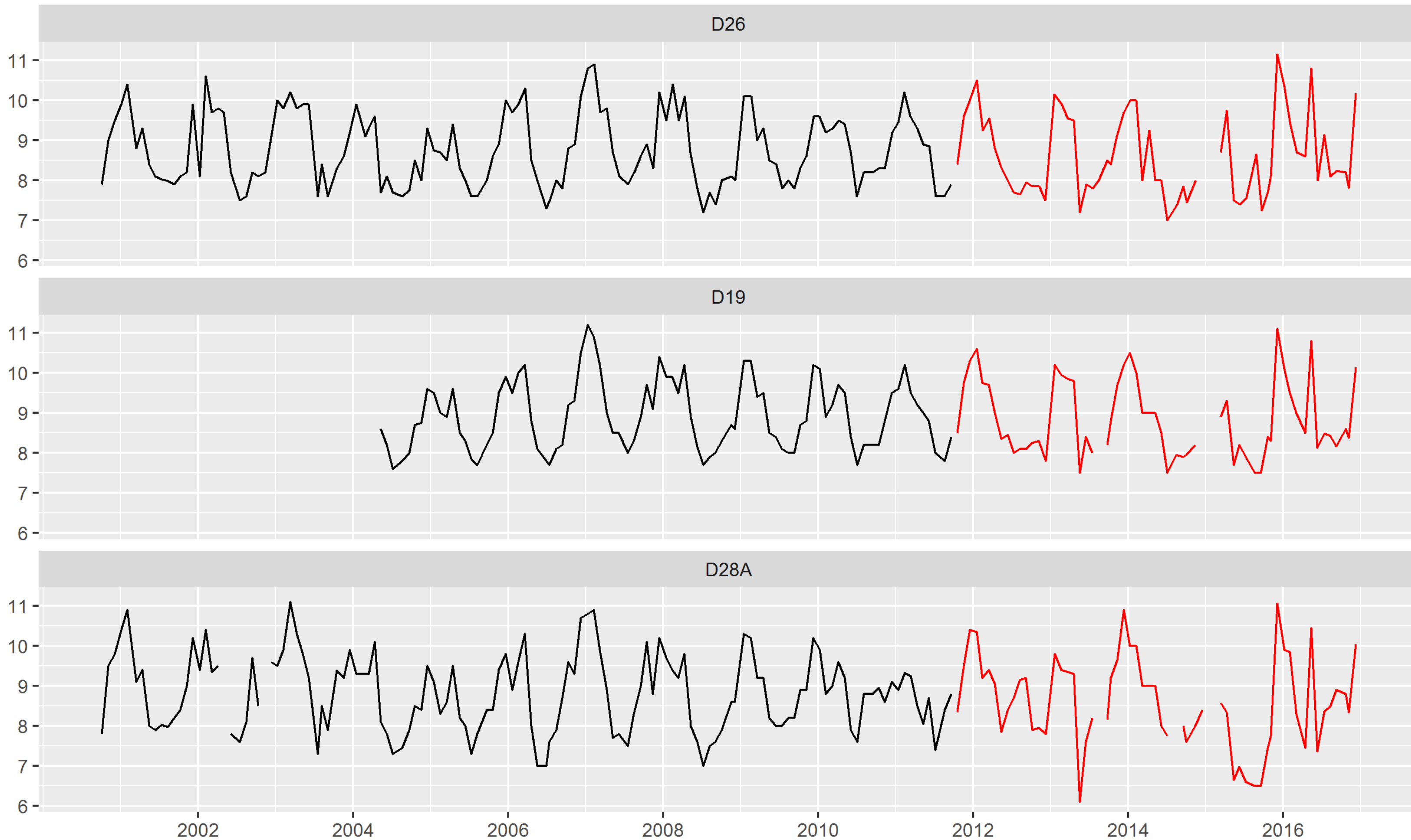

Figure 26. Time-series of DO (mg /L) at DWR-EMP water quality monitoring stations in the Central Delta, WY2001–2016.

The sites in this panel are on the flowpath of Sacramento River water towards the water pumps in the south Delta: D26 (San Joaquin River at Potato Point) D19 (Frank's Tract), D28 (Old River). Highlighted in red: most recent data from drought years (WY 2012–2016).

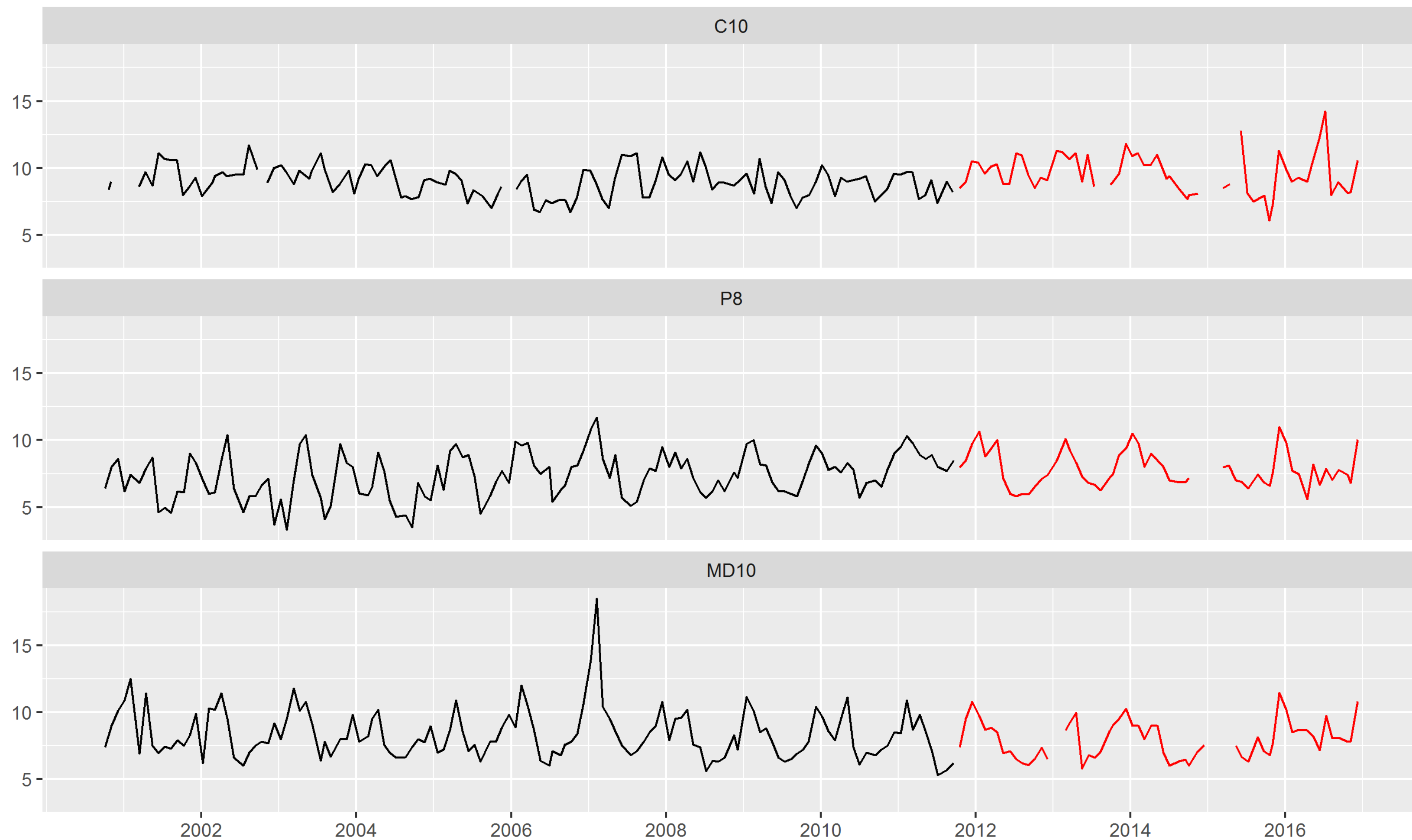

Figure 27. Time-series of DO (mg /L) at DWR-EMP water quality monitoring stations in the South Delta and North Central Delta, WY2001–2016.

The sites in this panel are along the flowpath of the San Joaquin River: C10 (San Joaquin River at Vernalis), P8 (San Joaquin River at Buckley Cove), and MD10 (Disappointment Slough). Highlighted in red: most recent data from drought years (WY 2012–2016).

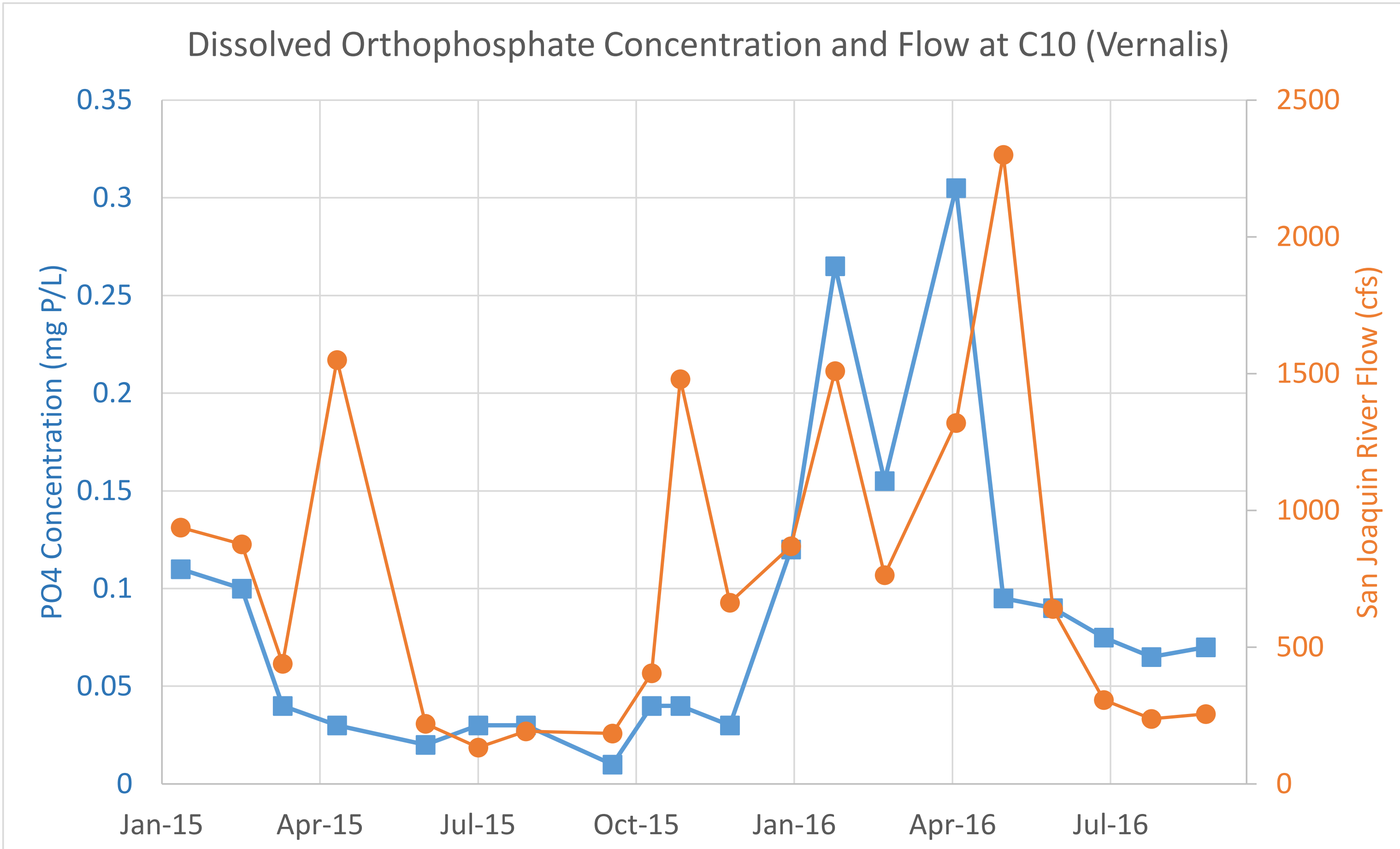

Figure 28. Dissolved orthophosphate concentrations at station C10 (Vernalis) and San Joaquin River Inflow (from DAYFLOW).

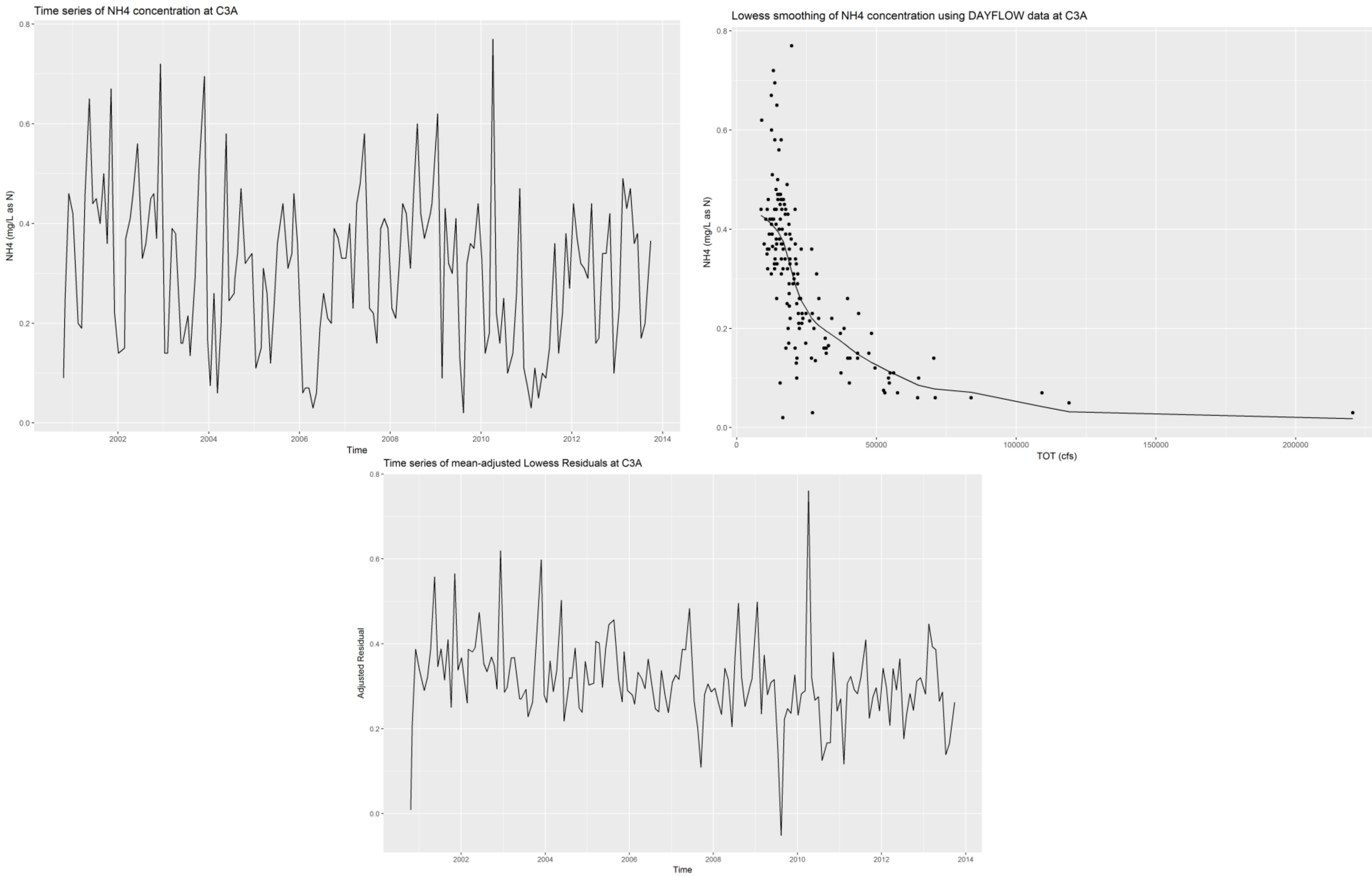

Figure 29: Flow adjusted concentration example for ammonium at station C3

Top left: Observed ammonium concentration time series. Top right: Relationship between inflow and concentration. Bottom: Flow adjusted concentration after accounting for expected changes based on flow.

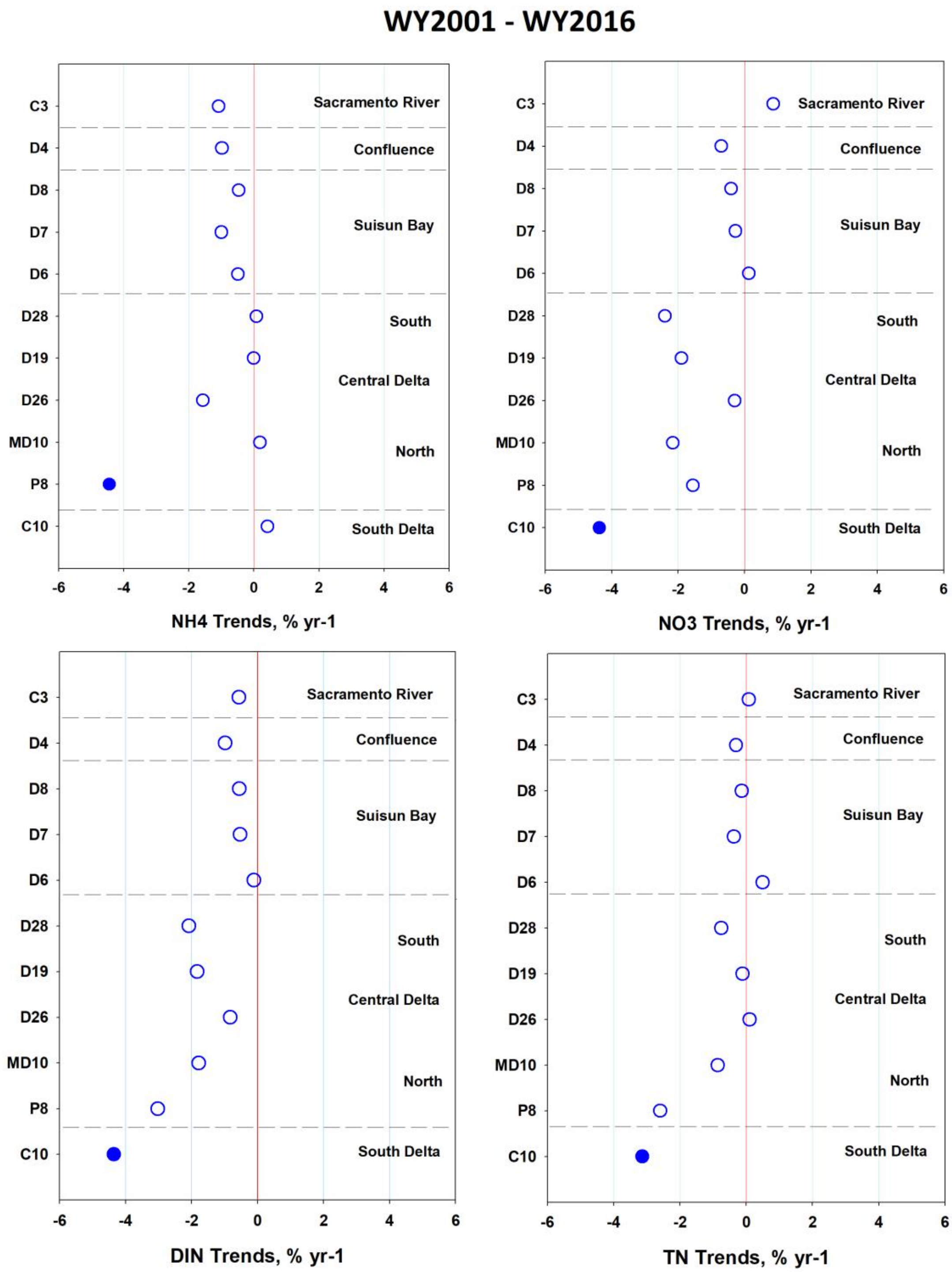

Figure 30. Magnitude (% change per year) of detected trends at DWR-EMP stations, WY 2001–2016 data (significance at $p \leq 0.05$), for NH_3, NO_3, DIN, and TN.

Percent change per year is the ratio of the Sen slope to the long-term median for each variable. Dark shaded circles indicate a statistically significant trend.

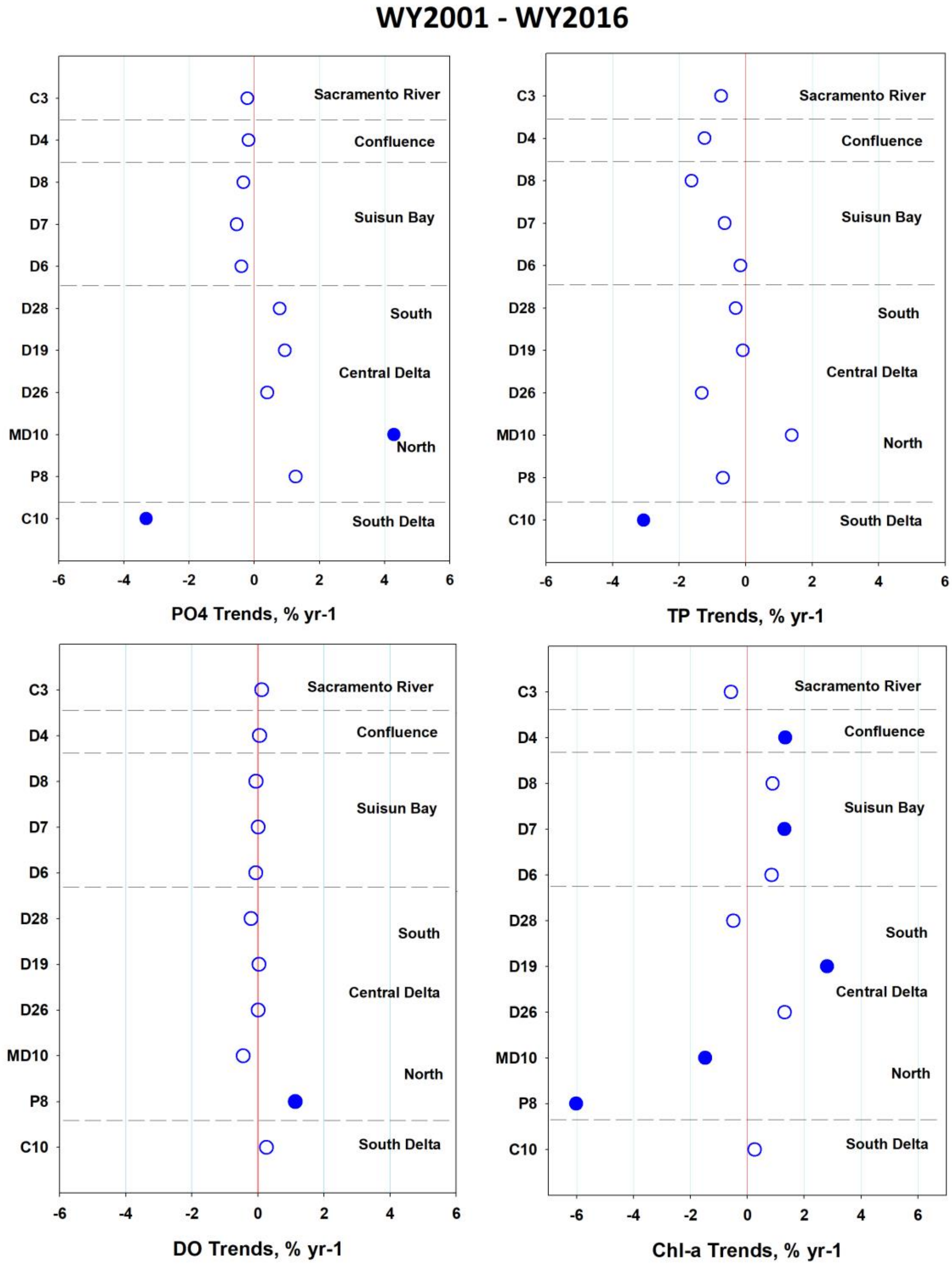

Figure 31. Magnitude (% change per year) of detected trends at DWR-EMP stations, WY 2001–2016 data (significance at $p \leq 0.05$), for PO_4, TP, DO, and Chl-a.

Percent change per year is the ratio of the Sen slope to the long-term median for each variable. Dark shaded circles indicate a statistically significant trend.

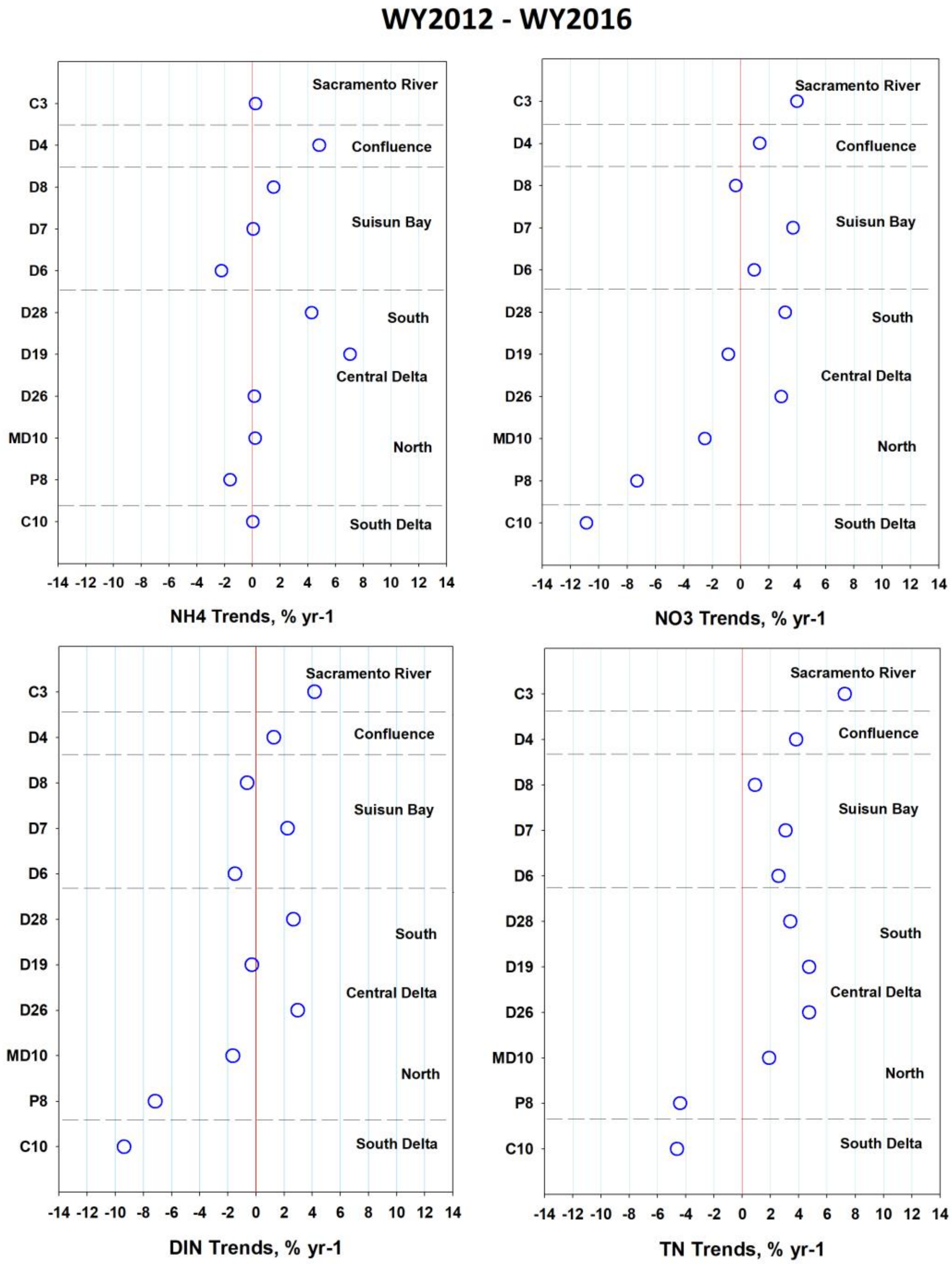

Figure 32. Magnitude (% change per year) of detected trends at DWR-EMP stations, WY 2012–WY2016 data (significance at $p \leq 0.05$), for NH3, NO_3, DIN, and TN.

Percent change per year is the ratio of the Sen slope to the long-term median for each variable. None of the trends was statistically significant.

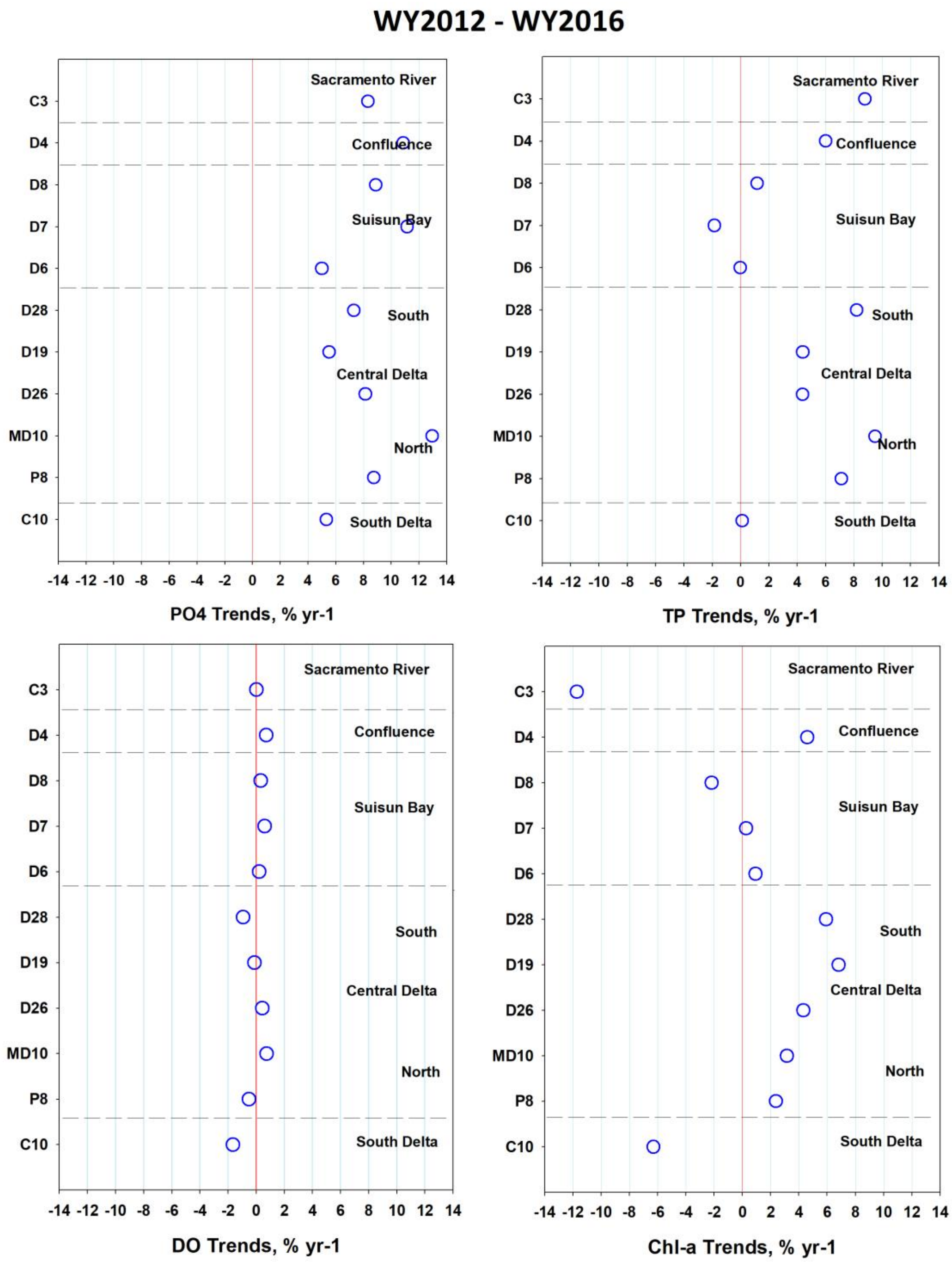

Figure 33. Magnitude (% change per year) of detected trends at DWR-EMP stations, WY 2012–2016 data (significance at $p \leq 0.05$), for PO_4, TP, DO, and Chl-a.

Percent change per year is the ratio of the Sen slope to the long-term median for each variable. None of the trends were statistically significant.

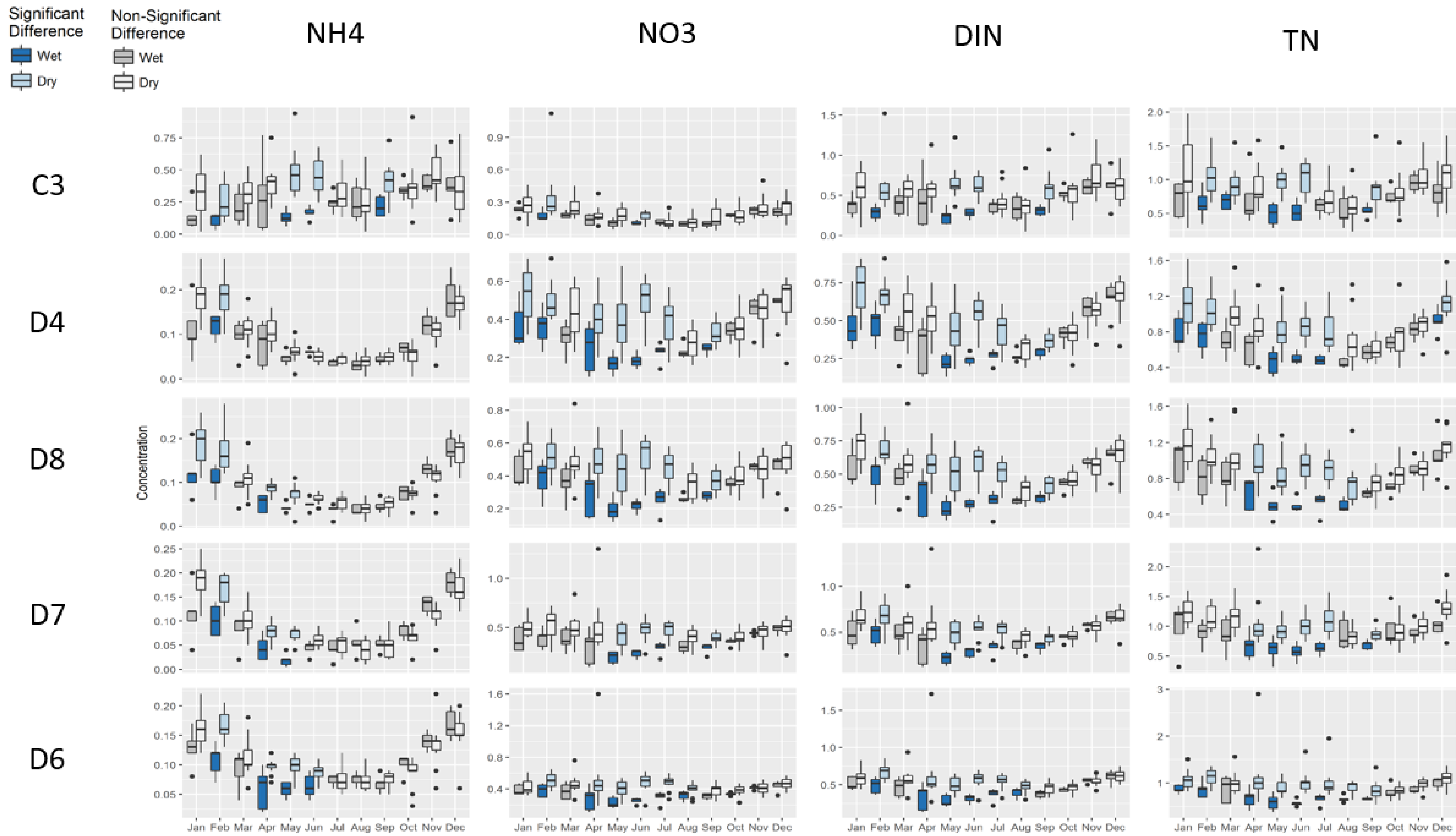

Figure 34. Comparison of NH_4, NO_3, DIN and TN concentrations in wet and dry years, WY2001–2016.

Boxplots for stations in the Sacramento River (C3), Confluence (D4), and Suisun Bay (D8, D7, D6). C3 (Sacramento River at Hood) is the site farthest upstream on the Sacramento River, D6 (Martinez) is the site farthest down-estuary in Suisun Bay. Concentrations are in mg N/L. The boxes show median concentration and 25th/75th percentiles, and the whiskers extend to 1.5x the interquartile range. Values outside this range are considered outliers and shown with dots. Note the varying y-axis scales. Colored boxes indicate statistically significant differences.

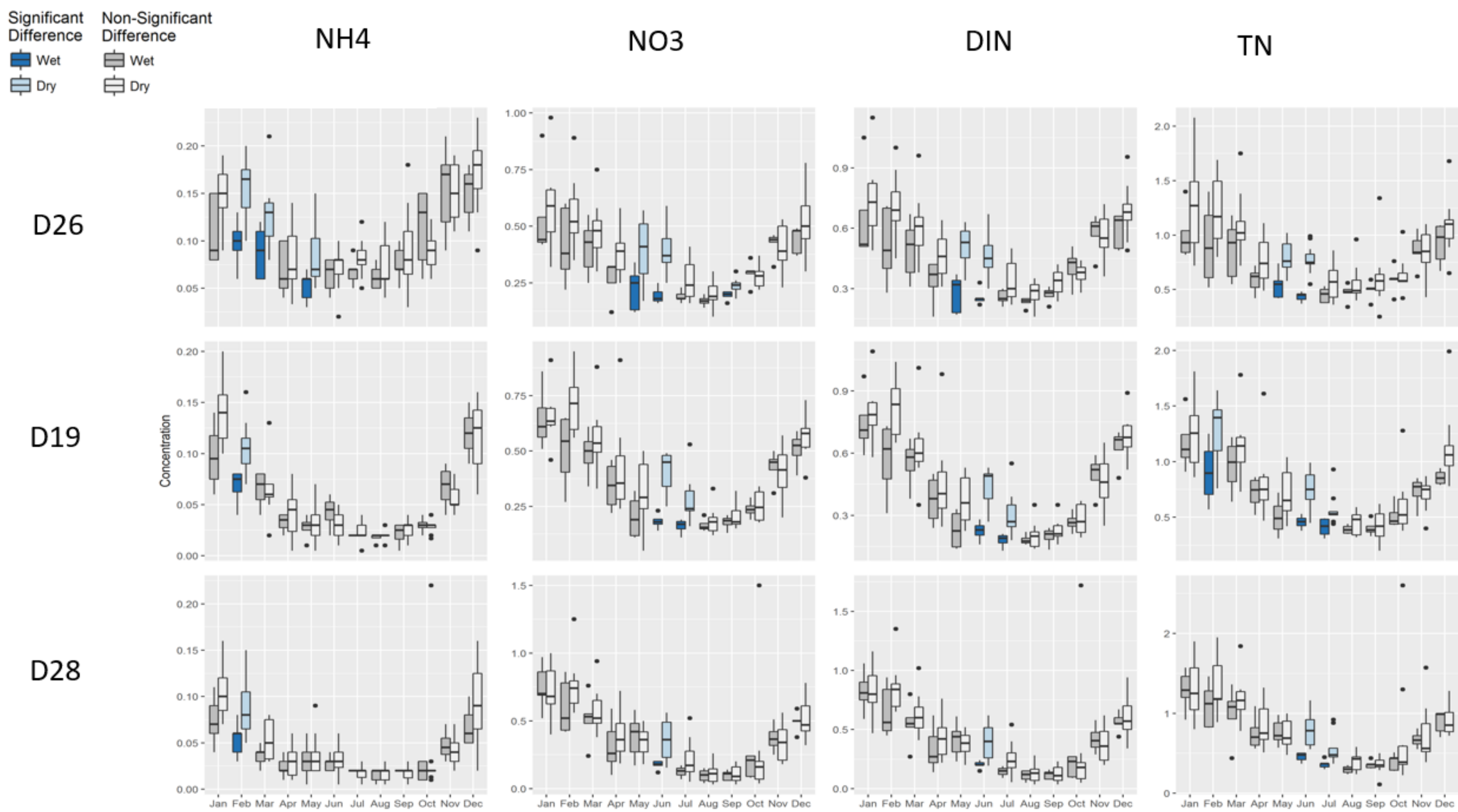

Figure 35. Comparison of NH_4, NO_3, DIN and TN concentrations in wet and dry years, WY2001–2016.

The sites in this panel are on the flowpath of Sacramento River water towards the water pumps in the south Delta: D26 (San Joaquin River at Potato Point) D19 (Frank's Tract), D28 (Old River). All concentrations are in mg N/L. The boxes show median concentration and 25th/75th percentiles, and the whiskers extend to 1.5x the interquartile range. Values outside this range are considered outliers and shown with dots. Note the varying y-axis scales. Colored boxes indicate statistically significant differences.

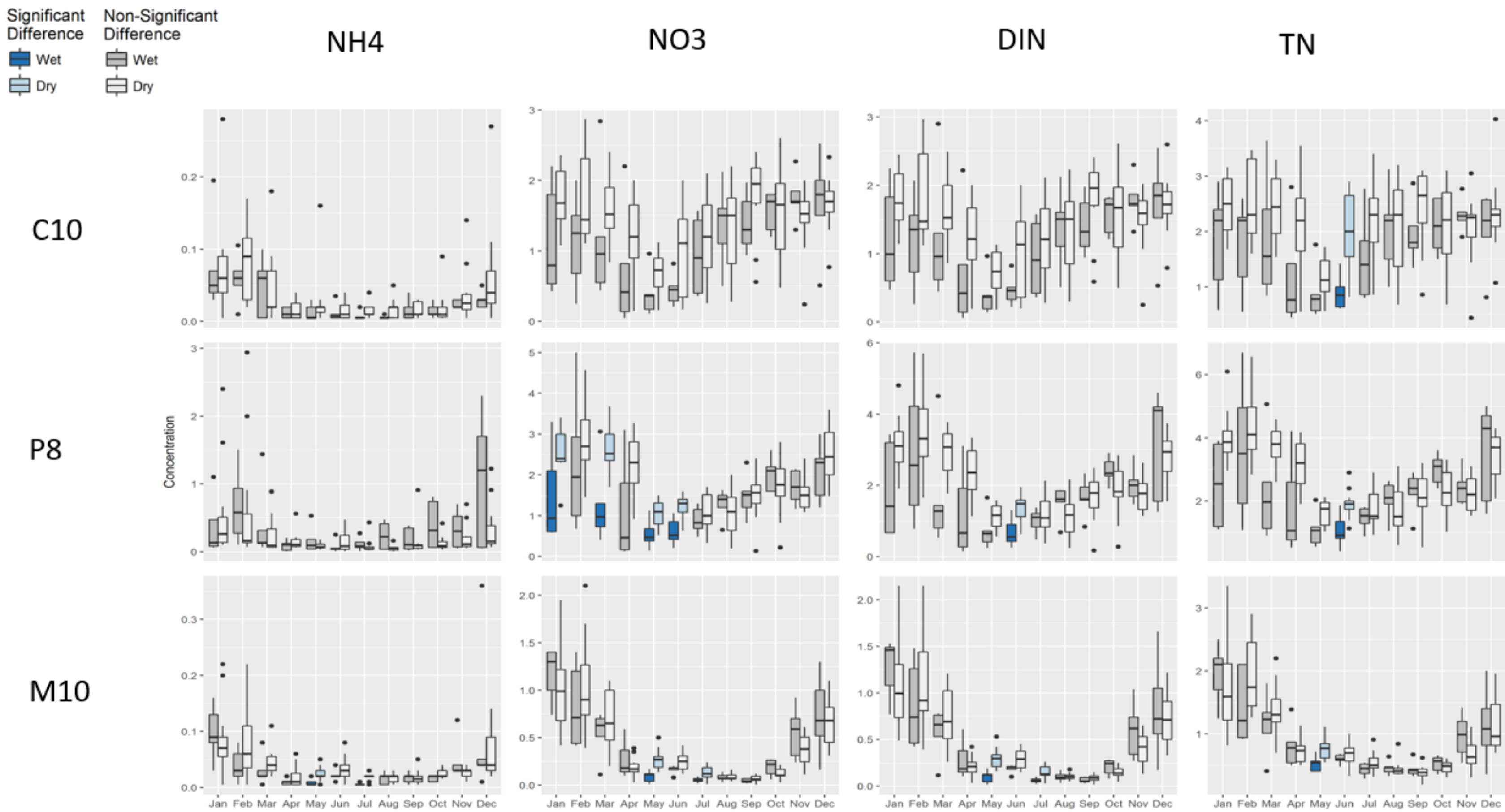

Figure 36. Comparison of NH_4, NO_3, DIN and TN concentrations in wet and dry years, WY2001–2016.

The sites in this panel are along the flowpath of the San Joaquin River: C10 (San Joaquin River at Vernalis), P8 (San Joaquin River at Buckley Cove), and MD10 (Disappointment Slough). All concentrations are in mg N/L. The boxes show median concentration and 25th/75th percentiles, and the whiskers extend to 1.5x the interquartile range. Values outside this range are considered outliers and shown with dots. Note the varying y-axis scales. Colored boxes indicate statistically significant differences.

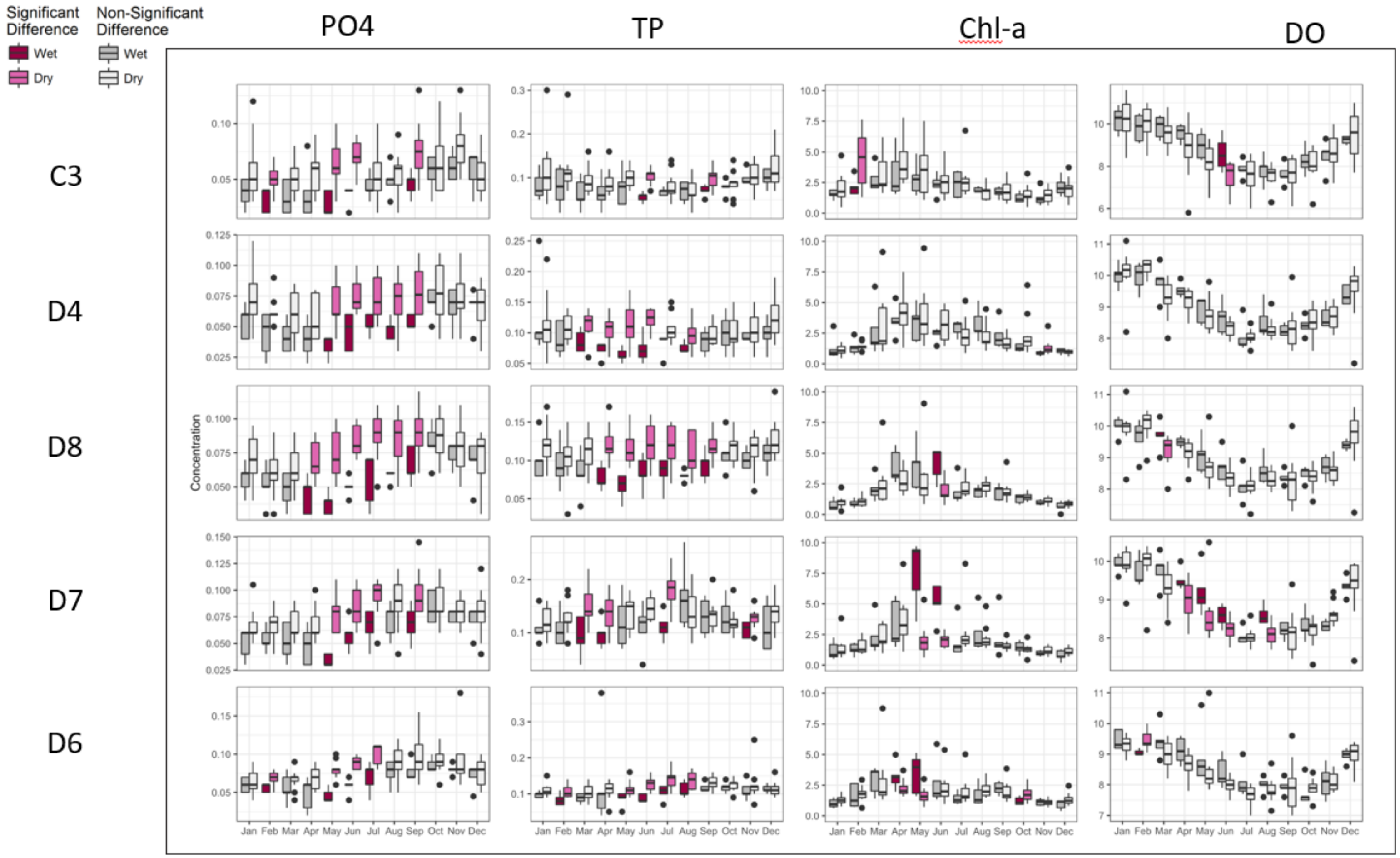

Figure 37. Comparison of PO_4, TP, chlorophyll-a, and DO concentrations in wet and dry years, WY2001–2016.

The boxplots are for stations in the Sacramento River (C3), Confluence (D4), and Suisun Bay (D8, D7, D6). C3 (Sacramento River at Hood) is the site farthest upstream on the Sacramento River, D6 (Martinez) is the site farthest down-estuary in Suisun Bay. Concentrations are in mg N/L. The boxes show median concentration and 25th/75th percentiles, and the whiskers extend to 1.5x the interquartile range. Values outside this range are considered outliers and shown with dots. Note the varying y-axis scales. Chl-a y-axis is truncated at 10 µg/L (not all values shown). Colored boxes indicate statistically significant differences.

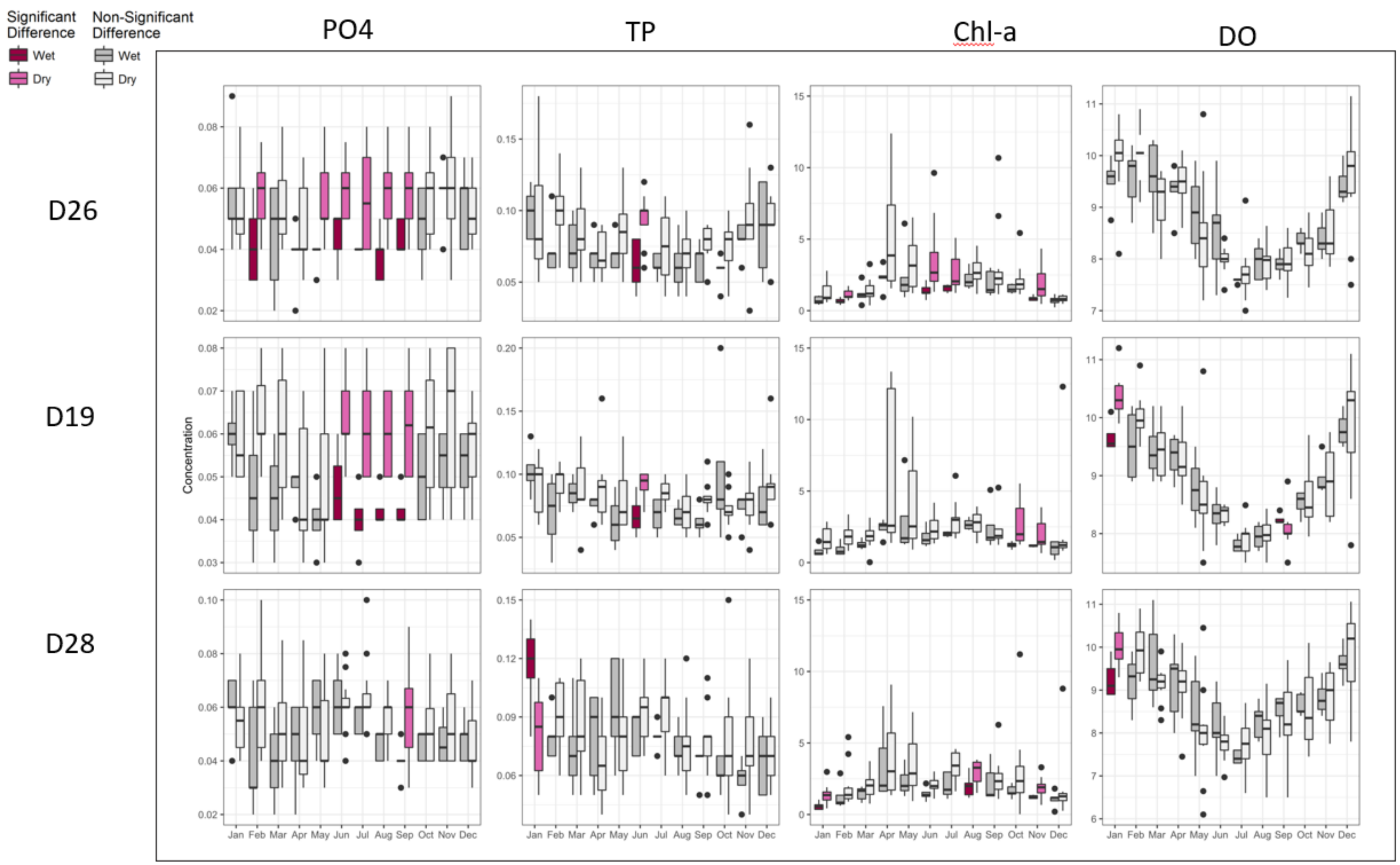

Figure 38. Boxplots for PO_4, TP, chlorophyll-a, and DO concentrations at DWR-EMP water quality monitoring stations in the Central Delta, WY2001–2016.

The data are grouped into two time periods, WY 2001–2011 and WY 2012–2016 (recent drought years). The sites in this panel are on the flowpath of Sacramento River water towards the water pumps in the south Delta: D26 (San Joaquin River at Potato Point) D19 (Frank's Tract), D28 (Old River). All concentrations are in mg N/L. The boxes show median concentration and 25th/75th percentiles, and the whiskers extend to 1.5x the interquartile range. Values outside this range are considered outliers and shown with dots. Note the varying y-axis scales. Chl-a y-axis is truncated at 15 µg/L (not all values shown). Colored boxes indicate statistically significant differences.

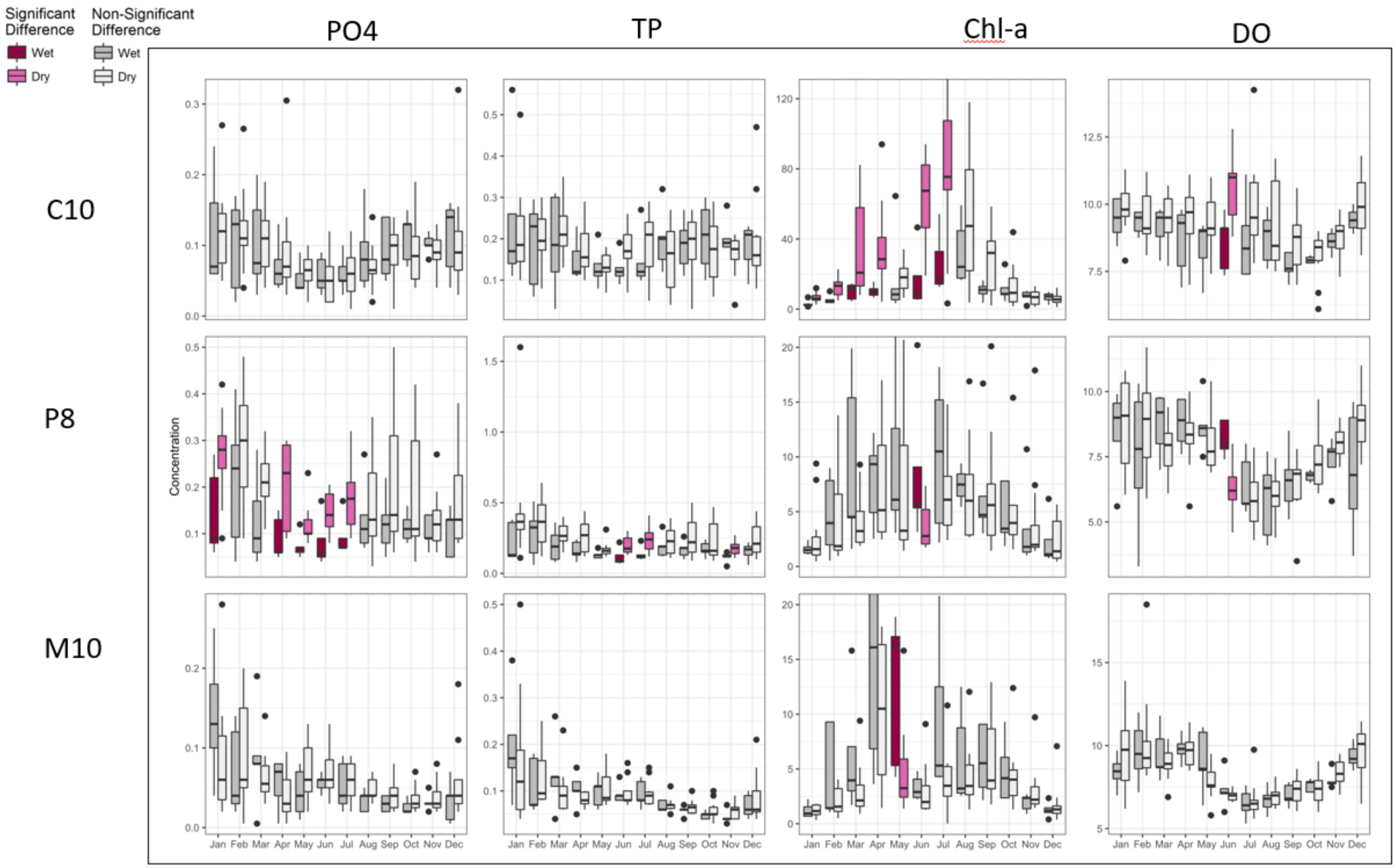

Figure 39. Comparison of PO_4, TP, chlorophyll-a, and DO concentrations in wet and dry years, WY2001–2016.

The boxplots are for stations in the South Delta and North Central Delta. The sites in this panel are along the flowpath of the San Joaquin River: C10 (San Joaquin River at Vernalis), P8 (San Joaquin River at Buckley Cove), and MD10 (Disappointment Slough). All concentrations are in mg N/L. The boxes show median concentration and 25th/75th percentiles, and the whiskers extend to 1.5x the interquartile range. Values outside this range are considered outliers and shown with dots. Note the varying y-axis scales. Chl-a y-axis is truncated at 120 and 20 µg/L (not all values shown). Colored boxes indicate statistically significant differences.

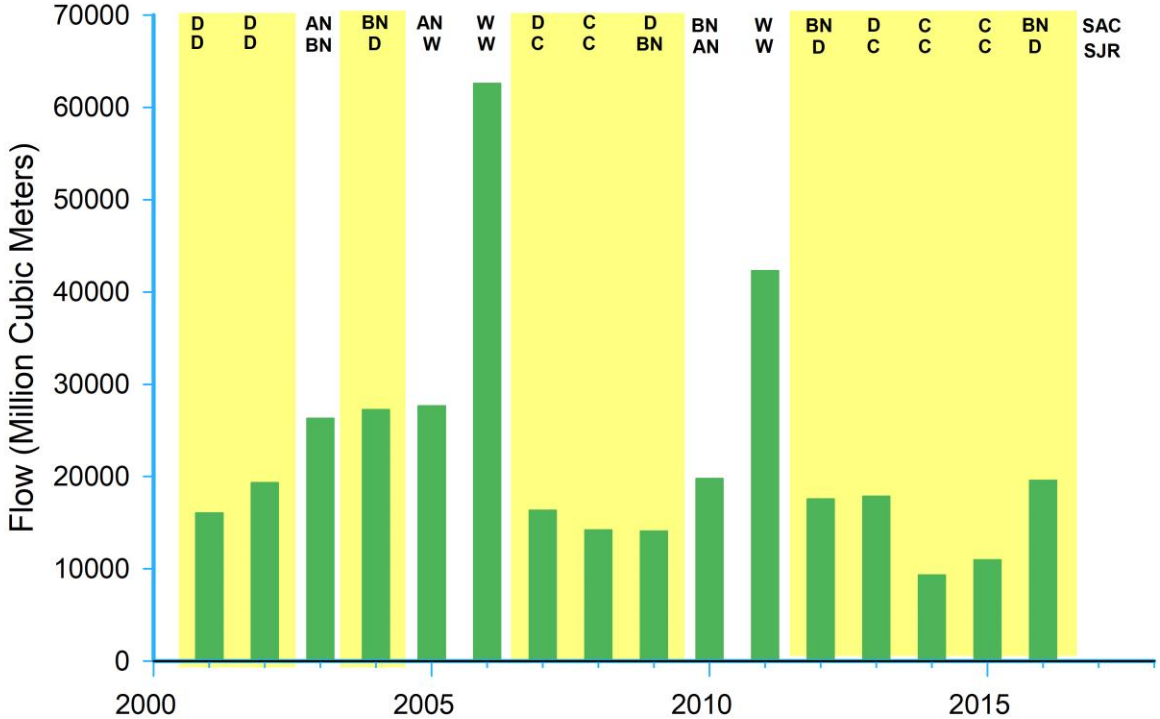

Figure 40. Freshwater inflow into the Delta.

Dry years based on the Water Year Hydrologic Classification Indices for the Sacramento Valley and San Joaquin Valley are highlighted in yellow.

Total annual inflow was calculated from Dayflow output for Total Delta Inflow. The Water Year Hydrologic Classification Indices are based on measured unimpaired runoff. The letters on the top of the graph represent the water year type for the Sacramento River (SAC) and the San Joaquin River (SJR):

AN = above normal year

BN = below normal year

C = critical year (very dry)

D = dry year

W = wet years

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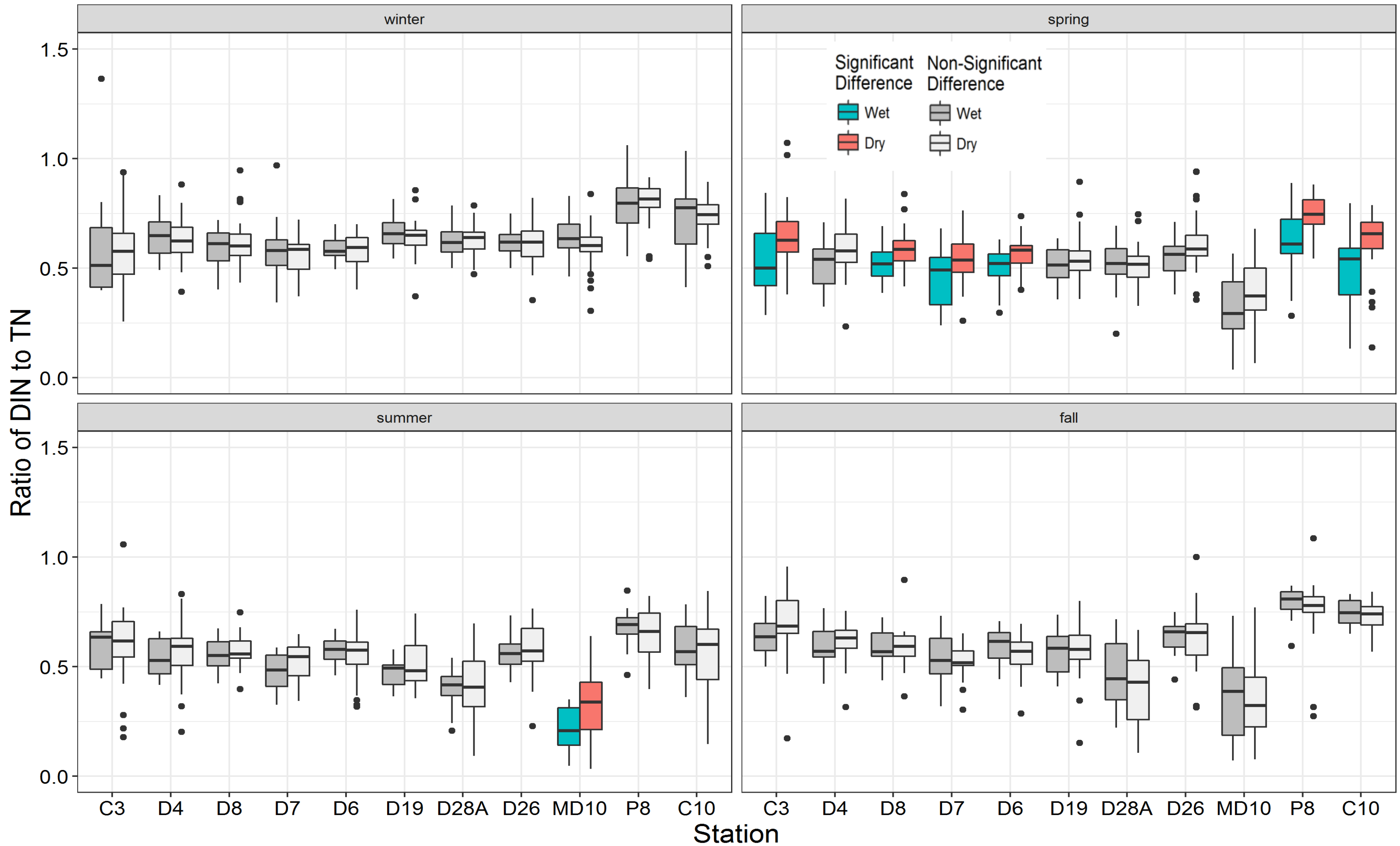

Figure 41. Ratio of DIN (mg N/L) vs. TN (mg/L), by season, dry years vs. normal and wet years.

Colored boxplots indicate a statistically significant difference between dry years and normal years at a station, based on the Kruskal-Wallis Test ($p \leq 0.05$). Wet and dry years are shown in Figure 40.

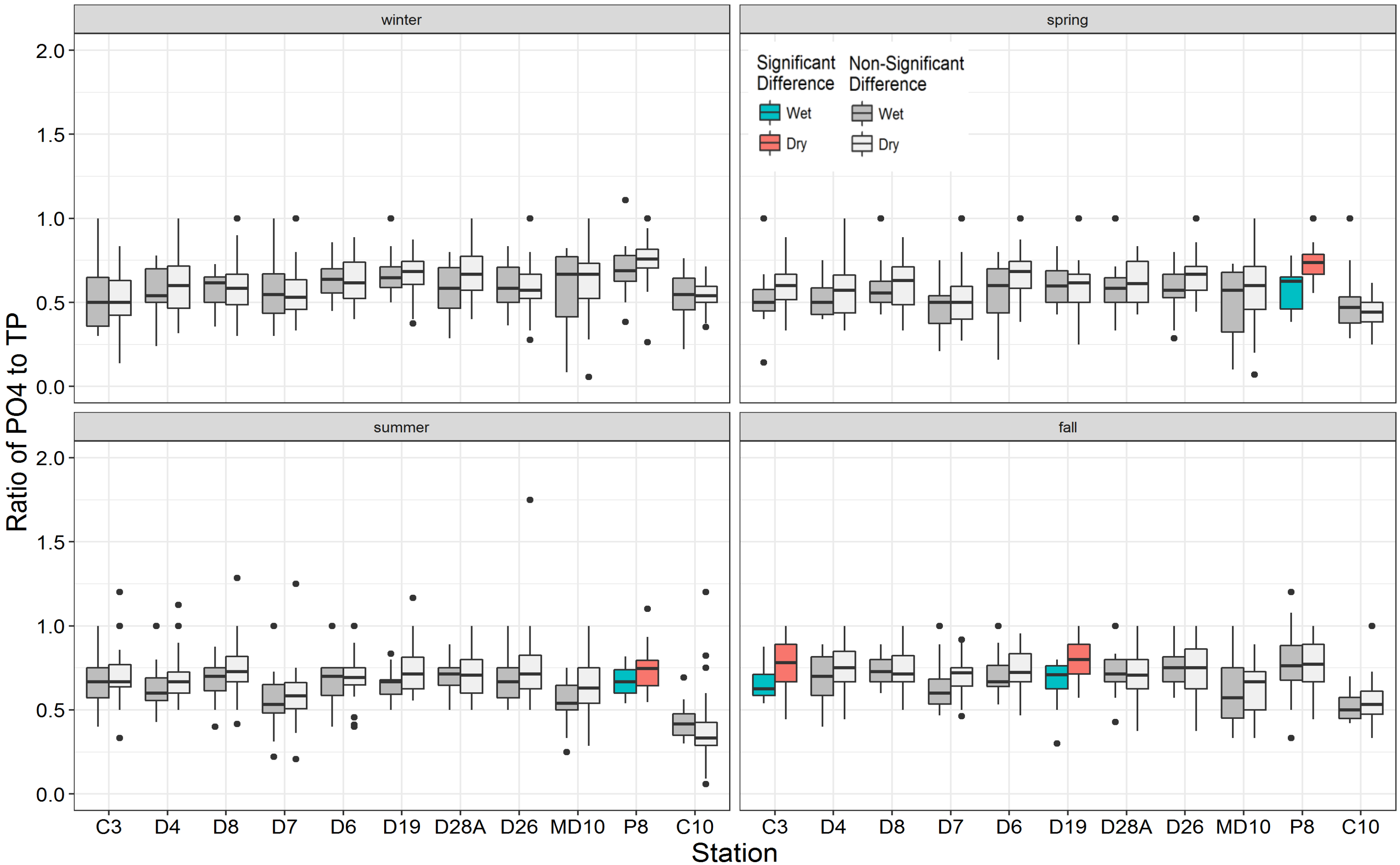

Figure 42. Ratio of PO_4 (mg P/L) vs. TP (mg/L), by season dry years vs. normal and wet years.

Colored boxplots indicate a statistically significant difference between dry years and normal years at a station, based on the Kruskal-Wallis Test ($p \leq 0.05$). Wet and dry years are shown in Figure 40.

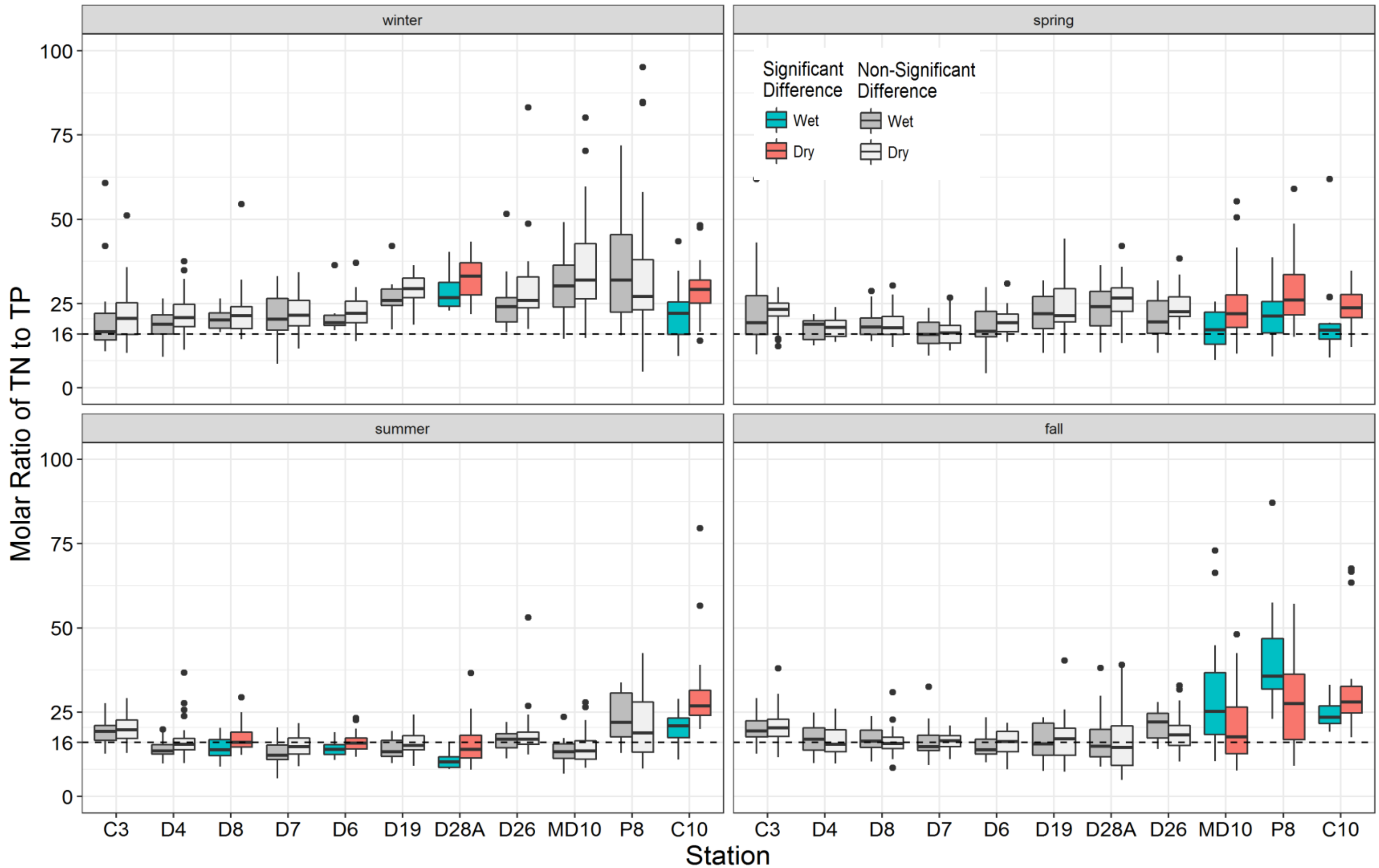

Figure 43. Molar ratio of N:P, by season, dry years vs. normal and wet years (see Figure 3).

Colored boxplots indicate a statistically significant difference between dry years and normal years at a station, based on the Kruskal-Wallis Test ($p \leq 0.05$).

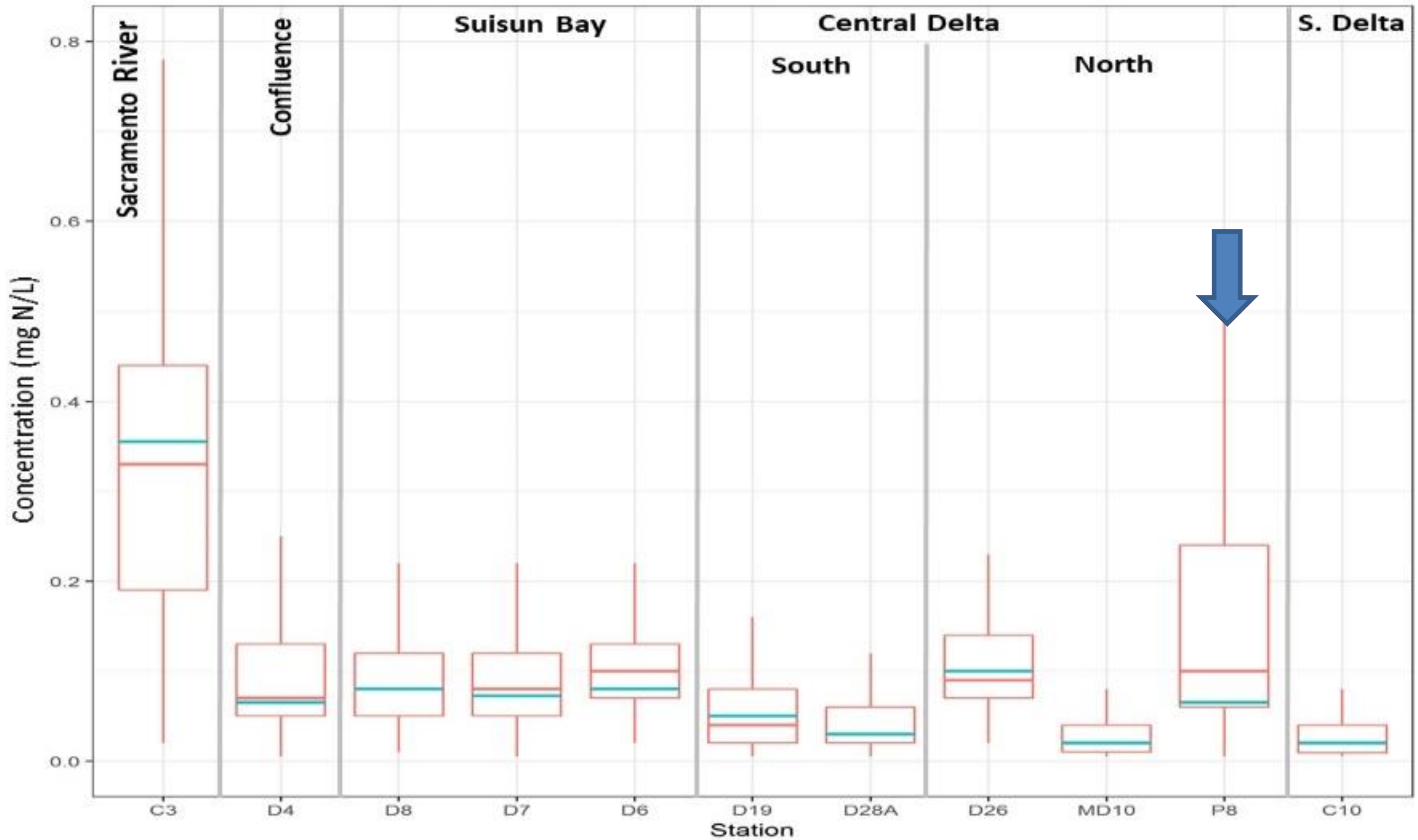

Figure 44. Distribution of NH_4 concentrations, by site, in the Delta and Suisun Bay.

The median values for 2016 data (blue bars) are shown for comparison with the entire dataset. The boxes show median concentration and 25th/75th percentiles, and the whiskers extend to 1.5x the interquartile range. Large arrows indicate the direction of statistically significant trends in WY2001–2016.

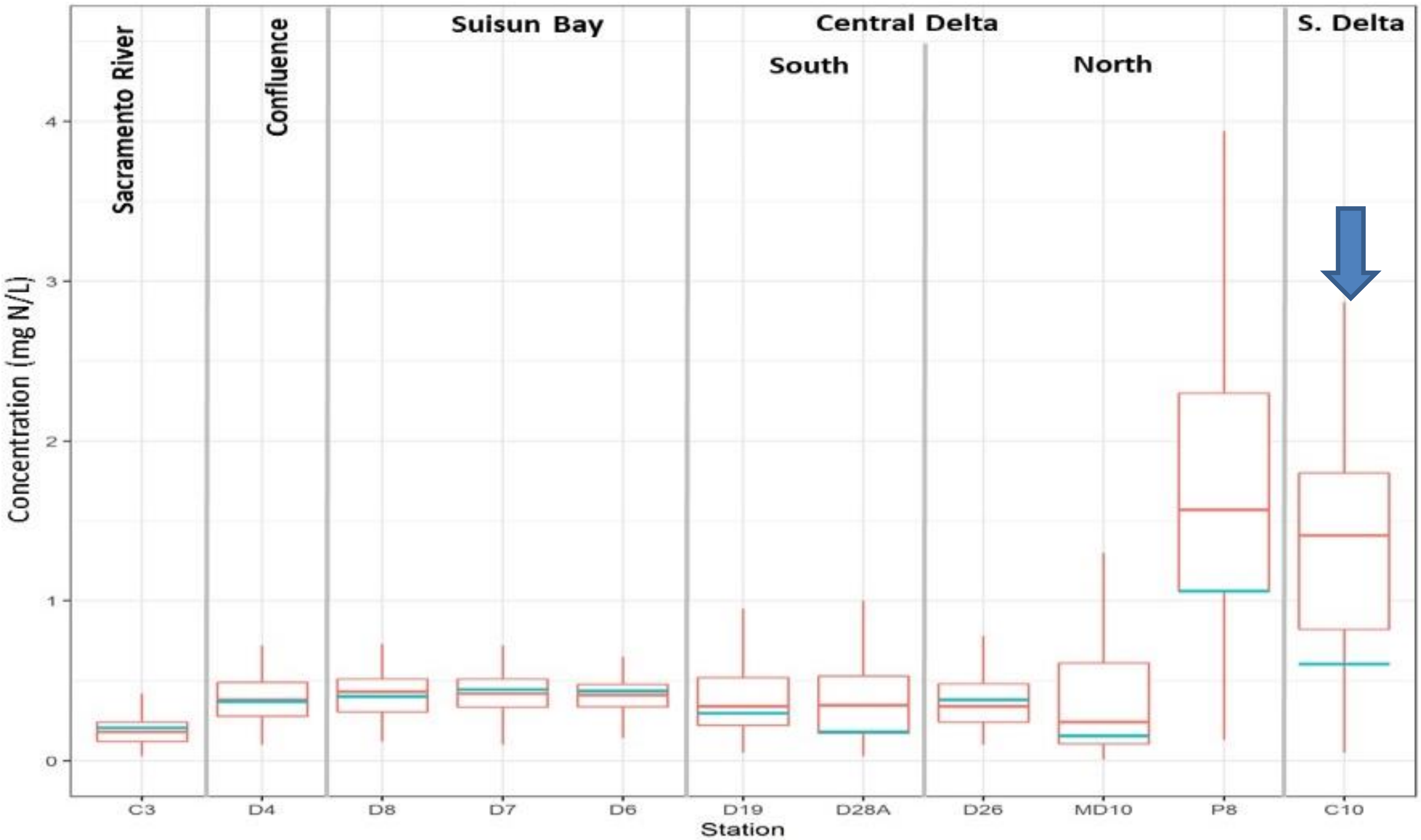

Figure 45. Distribution of NO_3 concentrations, by site, in the Delta and Suisun Bay.

The median values for 2016 data (blue bars) are shown for comparison with the entire dataset. The boxes show median concentration and 25th/75th percentiles, and the whiskers extend to 1.5x the interquartile range. Large arrows indicate the direction of statistically significant trends in WY2001–2016.

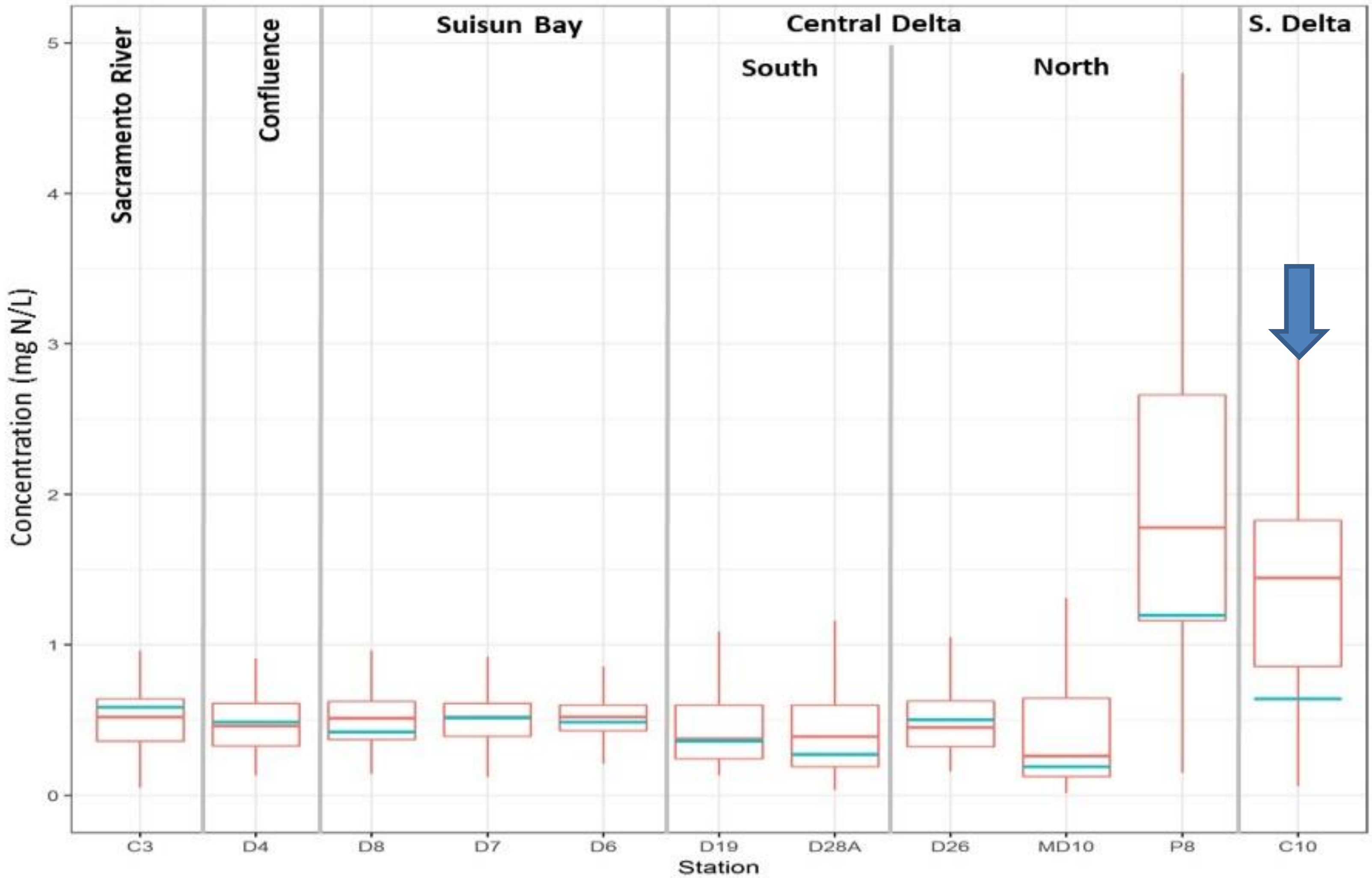

Figure 46. Distribution of DIN concentrations, by site, in the Delta and Suisun Bay.

The median values for 2016 data (blue bars) are shown for comparison with the entire dataset. The boxes show median concentration and 25th/75th percentiles, and the whiskers extend to 1.5x the interquartile range. Large arrows indicate the direction of statistically significant trends in WY2001–2016.

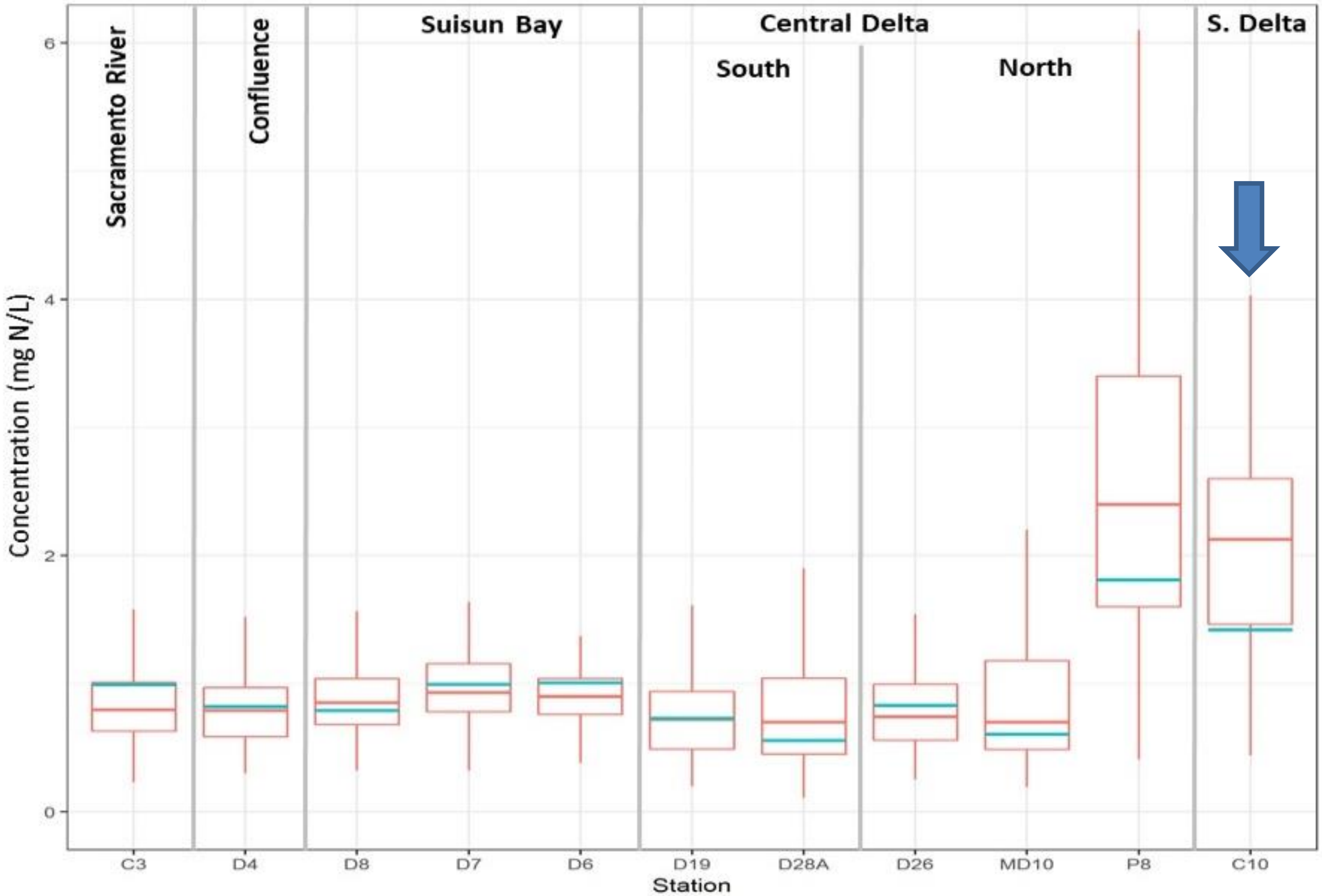

Figure 47. Distribution of TN concentrations, by site, in the Delta and Suisun Bay.

The median values for 2016 data (blue bars) are shown for comparison with the entire dataset. The boxes show median concentration and 25th/75th percentiles, and the whiskers extend to 1.5x the interquartile range. Large arrows indicate the direction of statistically significant trends in WY2001–2016.

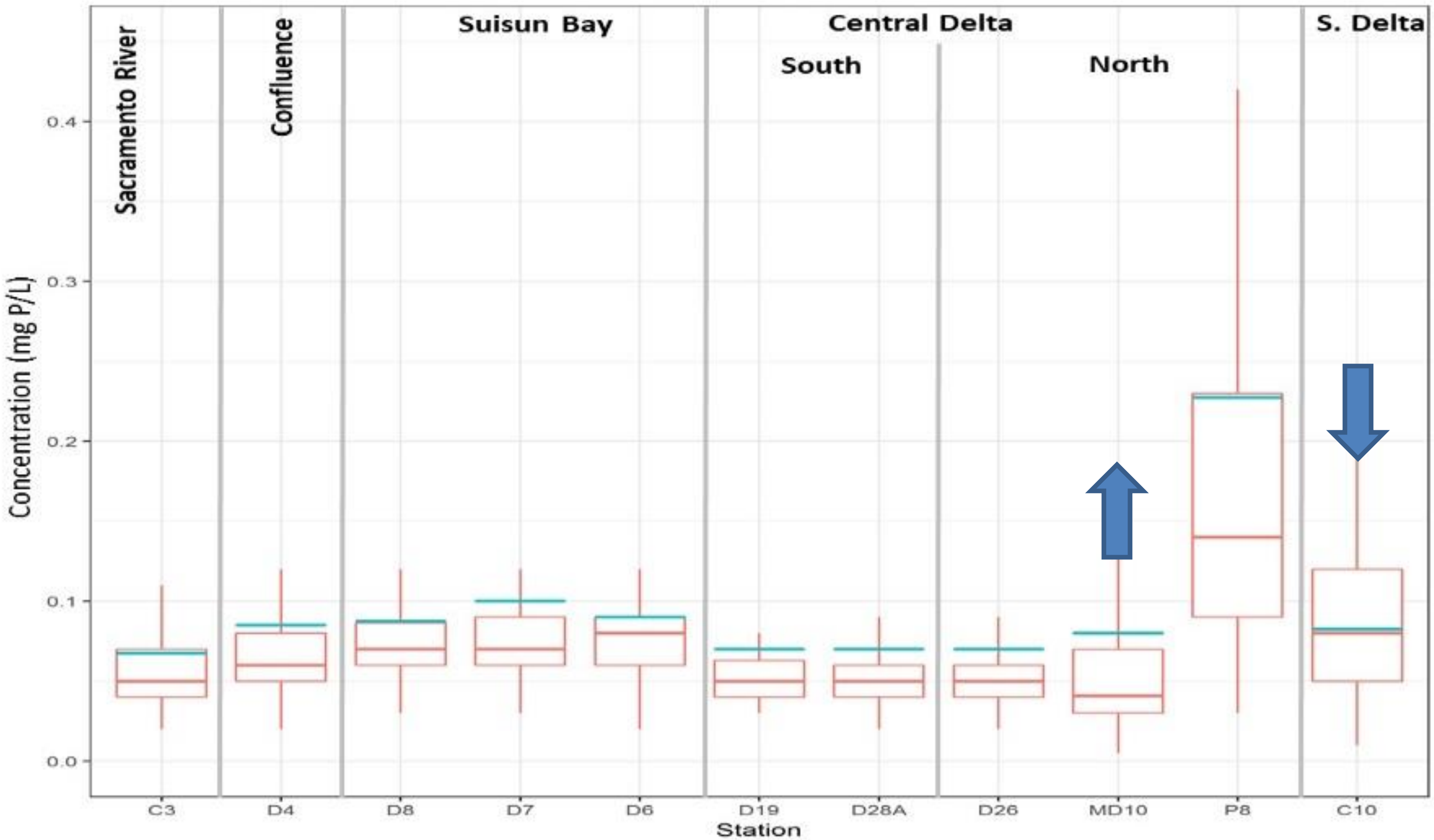

Figure 48. Distribution of PO_4 concentrations, by site, in the Delta and Suisun Bay.

The median values for 2016 data (blue bars) are shown for comparison with the entire dataset. The boxes show median concentration and 25th/75th percentiles, and the whiskers extend to 1.5x the interquartile range. Large arrows indicate the direction of statistically significant trends in WY2001–2016.

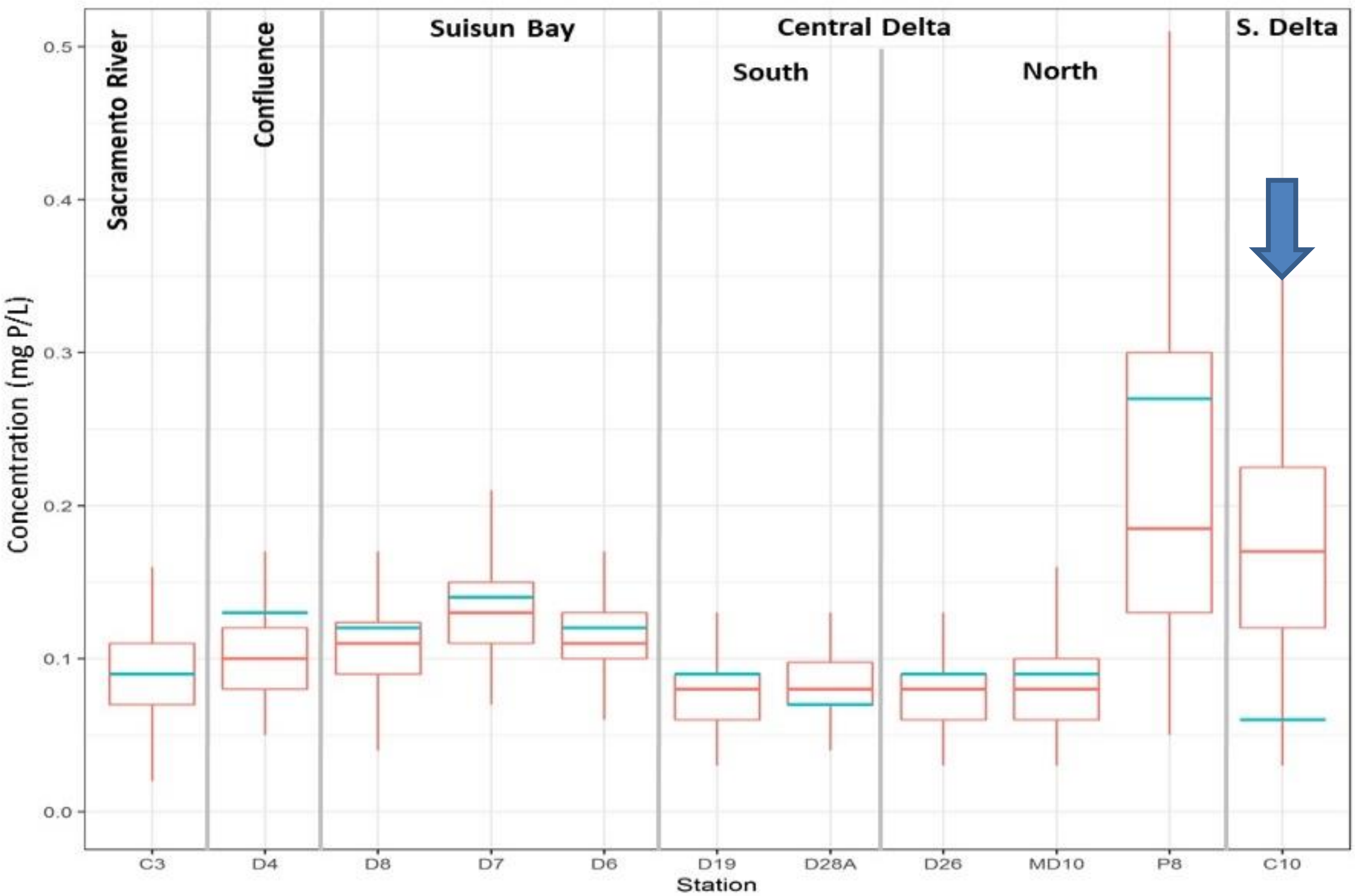

Figure 49. Distribution of TP concentrations, by site, in the Delta and Suisun Bay.

The median values for 2016 data (blue bars) are shown for comparison with the entire dataset. The boxes show median concentration and 25th/75th percentiles, and the whiskers extend to 1.5x the interquartile range. Large arrows indicate the direction of statistically significant trends in WY2001–2016.

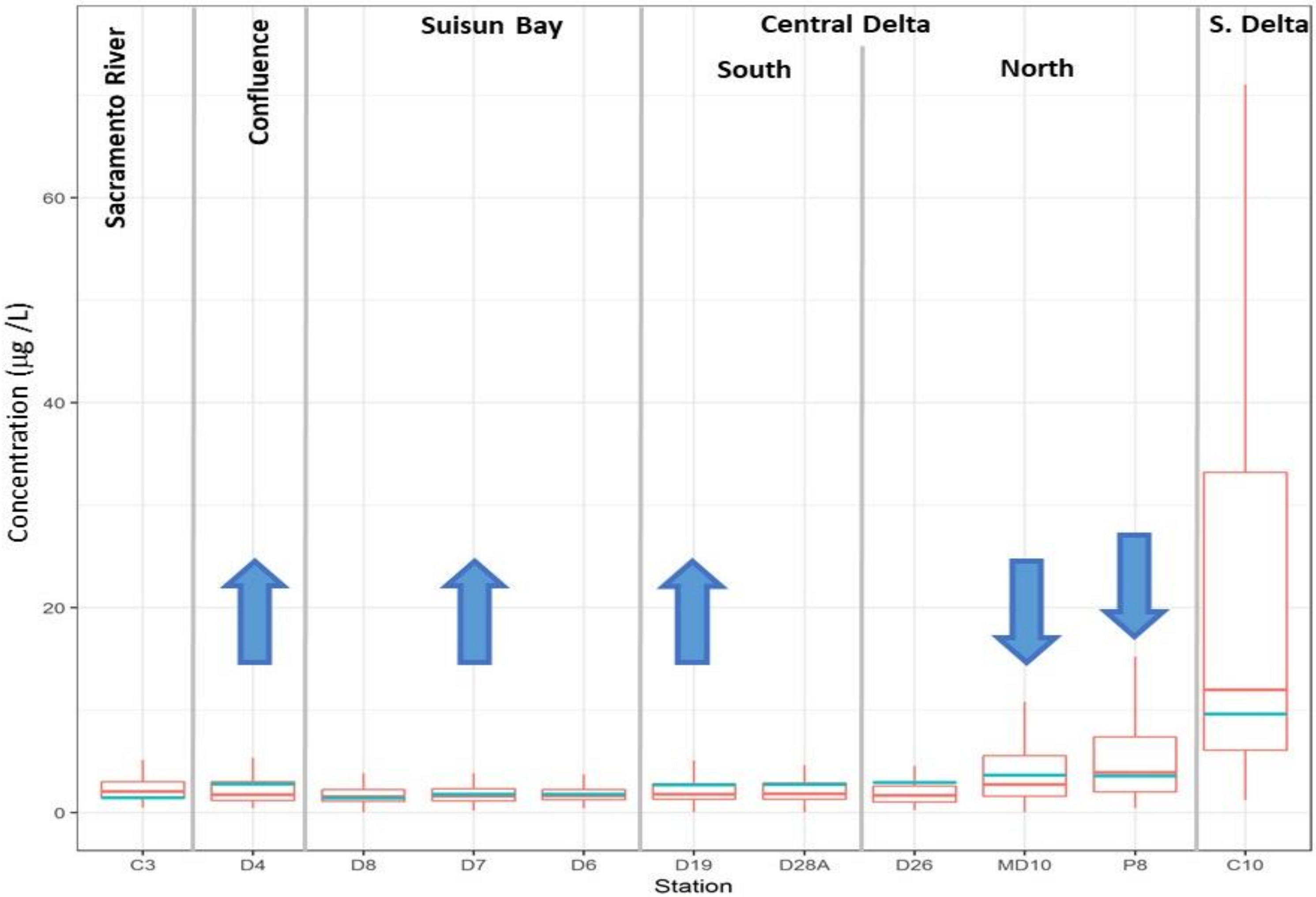

Figure 50. Distribution of chlorophyll-a concentrations, by site, in the Delta and Suisun Bay.

The median values for 2016 data (blue bars) are shown for comparison with the entire dataset. The boxes show median concentration and 25th/75th percentiles, and the whiskers extend to 1.5x the interquartile range. Large arrows indicate the direction of statistically significant trends in WY2001–2016.

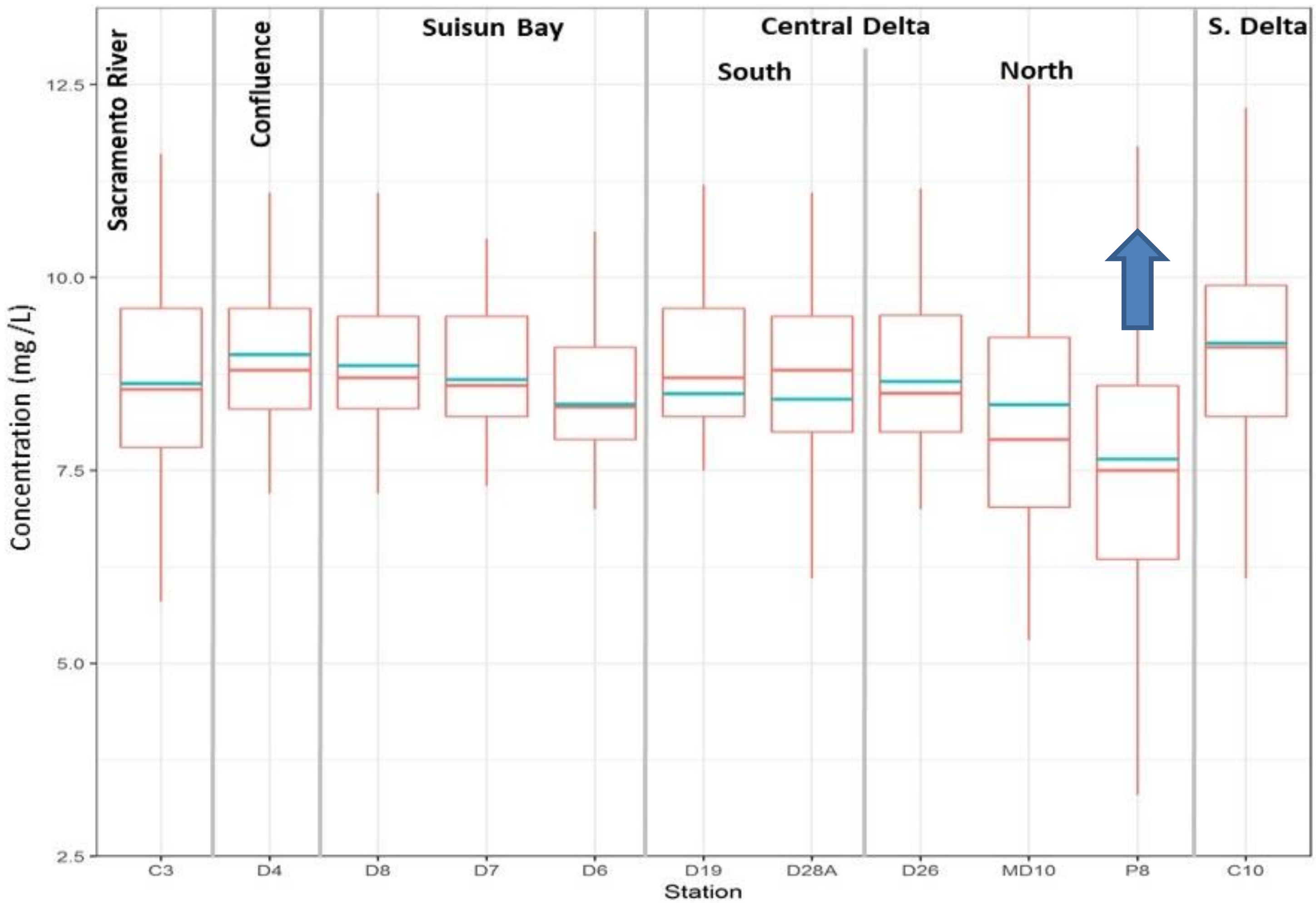

Figure 51. Distribution of DO concentrations, by site, in the Delta and Suisun Bay.

The median values for 2016 data (blue bars) are shown for comparison with the entire dataset. The boxes show median concentration and 25th/75th percentiles, and the whiskers extend to 1.5x the interquartile range. Large arrows indicate the direction of statistically significant trends in WY2001–2016.

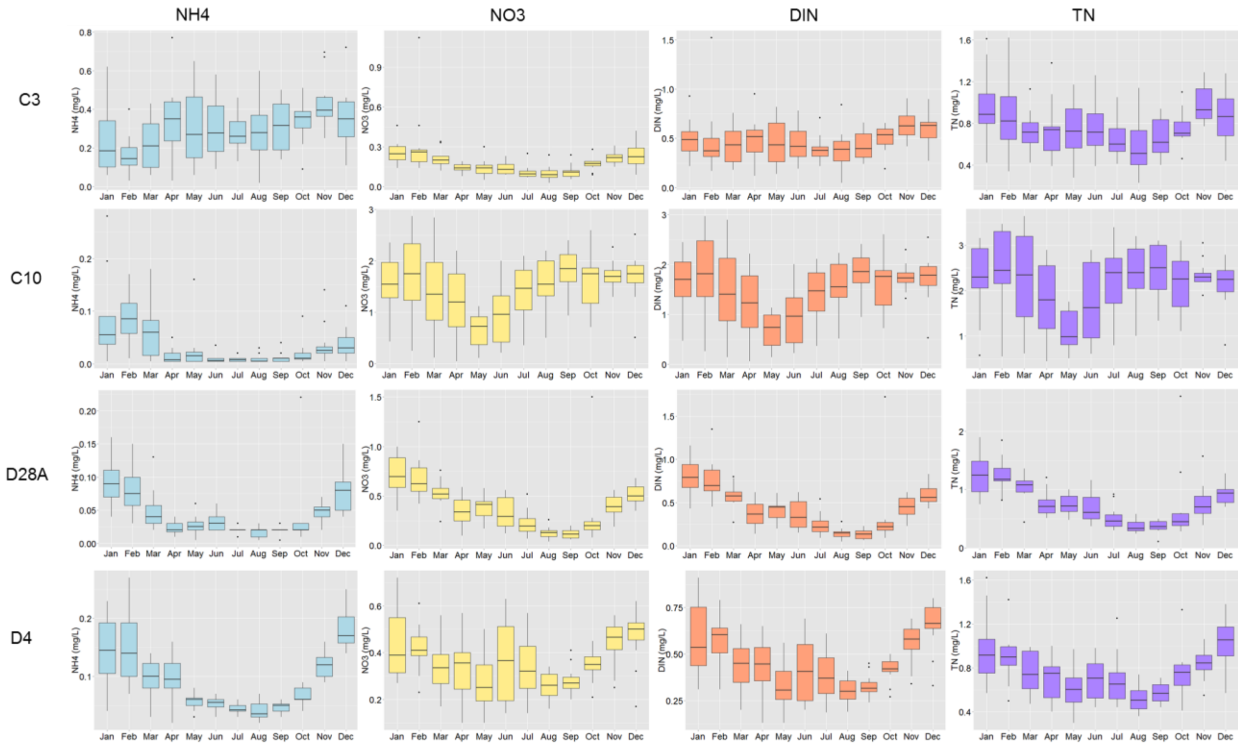

Figure 52. Box and whisker plots of NH_4, NO_3, DIN and TN concentrations at a subset of DWR-EMP stations (data ranging from 2001 to 20011).

The four stations represent the spatial and seasonal variability in concentrations of different nitrogen forms in the Delta. The boxes show median concentration and 25th/75th percentiles, and the whiskers extend to 1.5x the interquartile range. Dots represent outliers. Note the varying y-axis scales. From Novick et al. (2015).

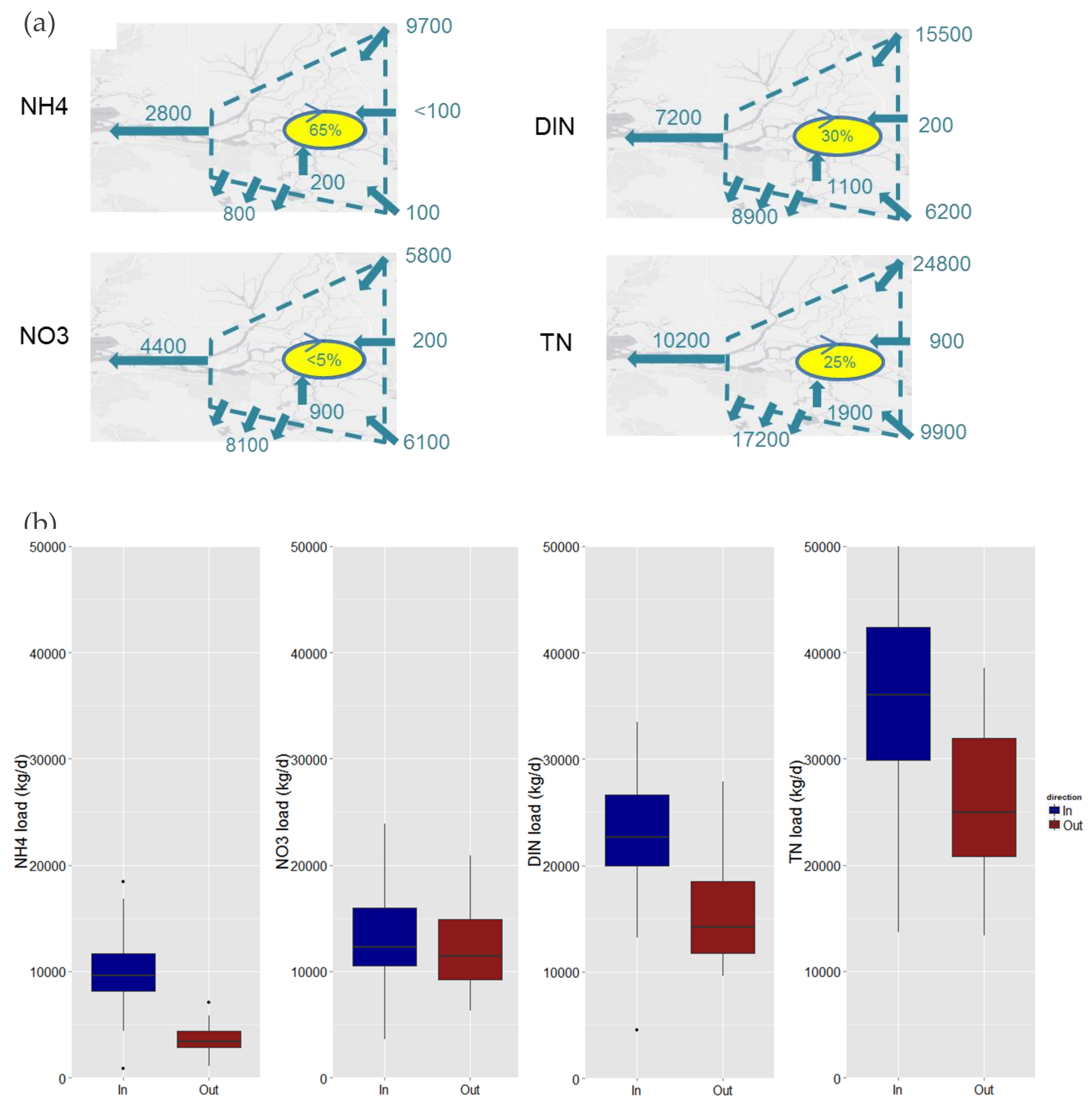

Figure 53. (a) Average summer (Jun-Oct) Delta-scale mass balance results for NH_4, NO_3, DIN and TN for the period 2006–2011. (b) Boxplots of 1-box model results (loads into and out of the Delta) for NH_4, NO_3, DIN and TN for the period 2006–2011.

Boxplots show the median and 25th/75th percentile, and the whiskers extend to 1.5x the interquartile range. Mass balance calculations for Suisun Bay were performed and can be found in Appendix 3 of Novick et al. (2015). All units are kg N-day. From Novick et al. (2015).

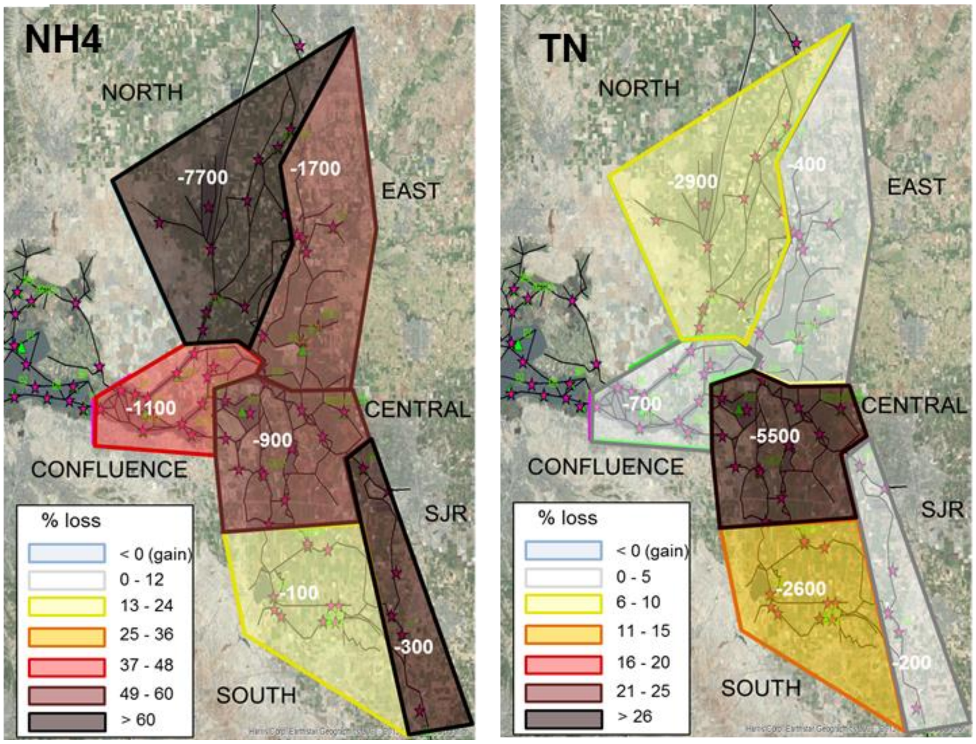

Figure 54. Average nitrogen loss within each subregion of the DSM2 model, for June-October of 2006–2011.

Color indicates % loss in each region (note different scales for % loss categories). Mass losses are in units of kg N/day. From Novick et al. (2015).

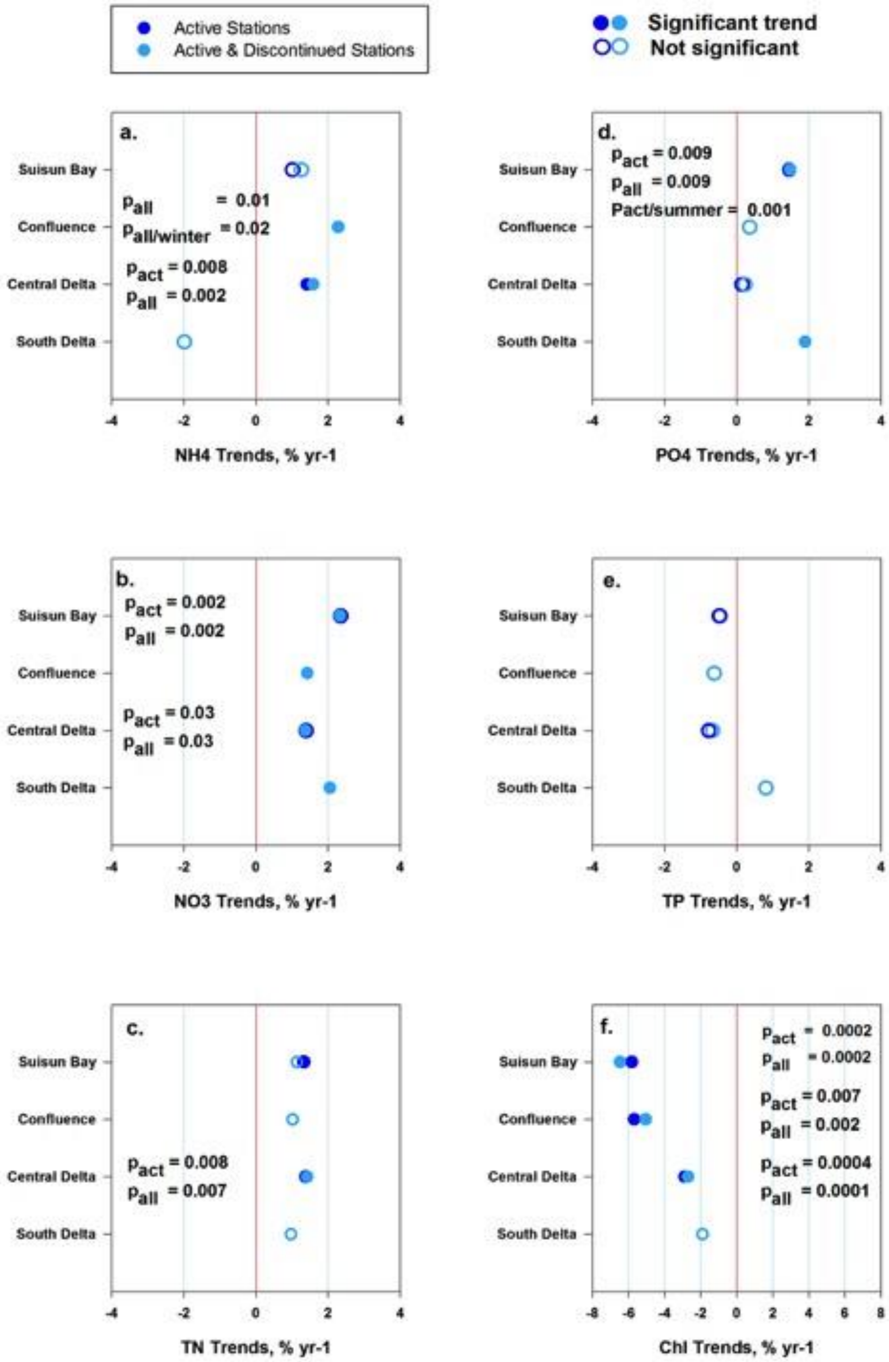

Figure 55. Comparison of detected trends at active DWR-EMP stations and all stations (active plus discontinued), 1975–95 data (significance at $p \leq 0.05$), for ammonium (NH_4), nitrate (NO_3), total nitrogen (TN), dissolved orthophosphate (PO_4), total phosphorus (TP,) and chlorophyll-a (Chl).

Trends are expressed as the Sen slope divided by the long-term median for each subregion.

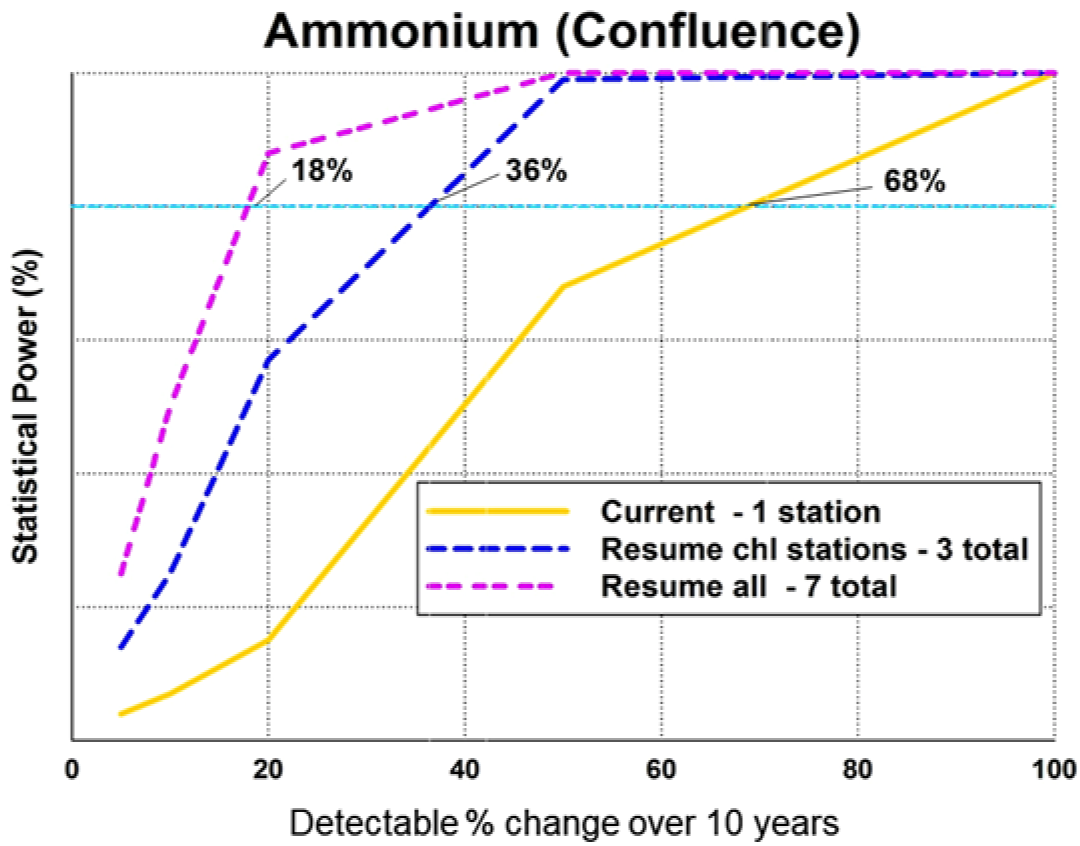

Figure 56. In the Confluence region, resuming NH_4 monitoring at all historic stations would considerably increase the sensitivity for long-term trend detection.

Results of a power analysis suggest that an 18% change over 10 years would be detectable if monitoring were resumed at all historic stations. The horizontal blue dotted line represents 80% power, which is a widely accepted threshold for trend detection.

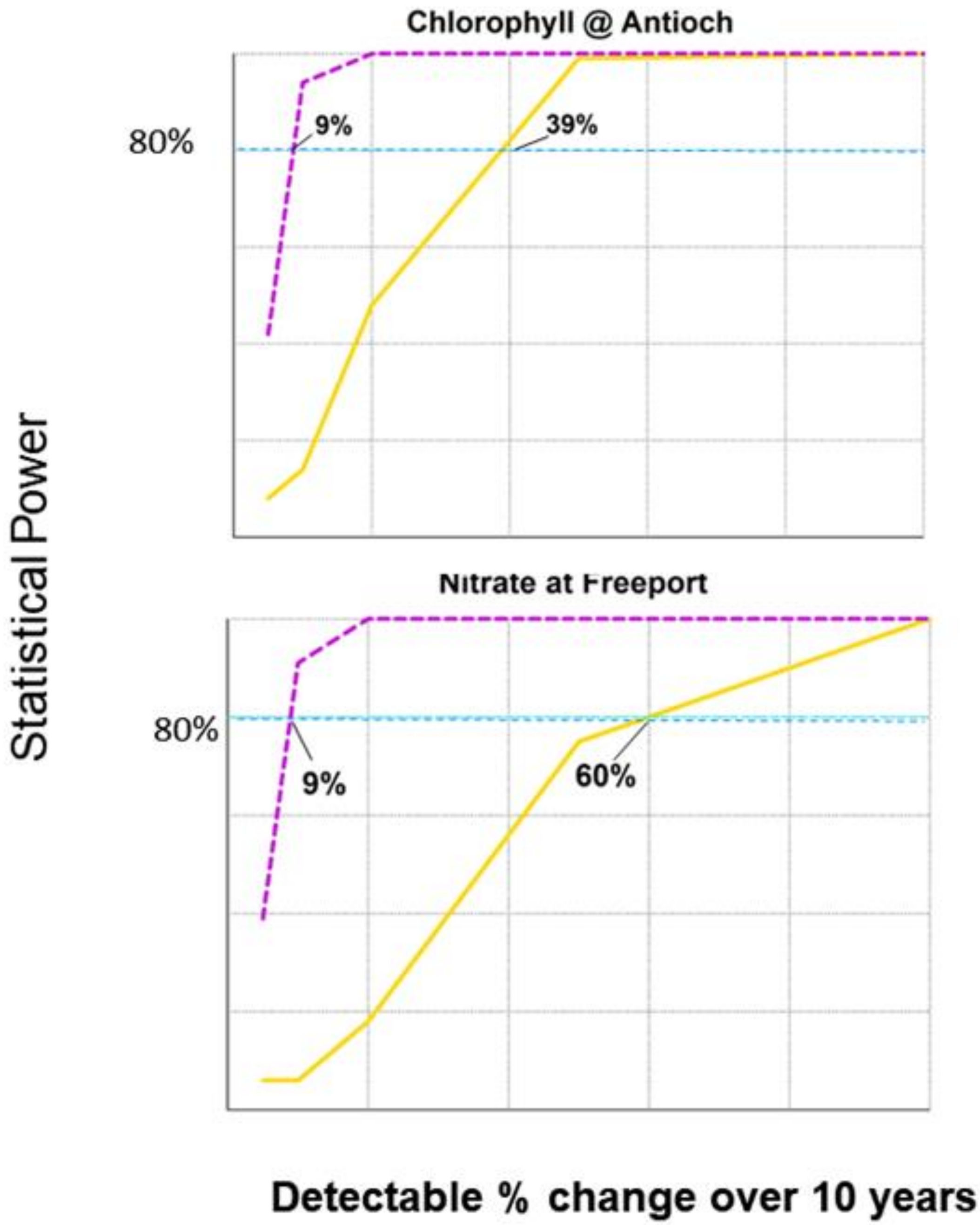

Figure 57. Comparison of power curves for the detection of long-term trends from discrete grab sampling and continuous sensor monitoring data.

The yellow solid lines represent discrete data and the pink dotted lines represent continuous sensor data. The upper graph is for chlorophyll-a at San Joaquin River at Antioch. The lower graph is for NO_3 at Sacramento River at Freeport (FPT). The results suggest that continuous sensor monitoring would be able to detect a 9% change over 10 years for both parameters, compared to a detectable change of 39% in chlorophyll-a concentrations and 60% change in nitrate that could be achieved with discrete monitoring. The blue dotted line represents 80% power, which is a widely accepted threshold for trend detection.

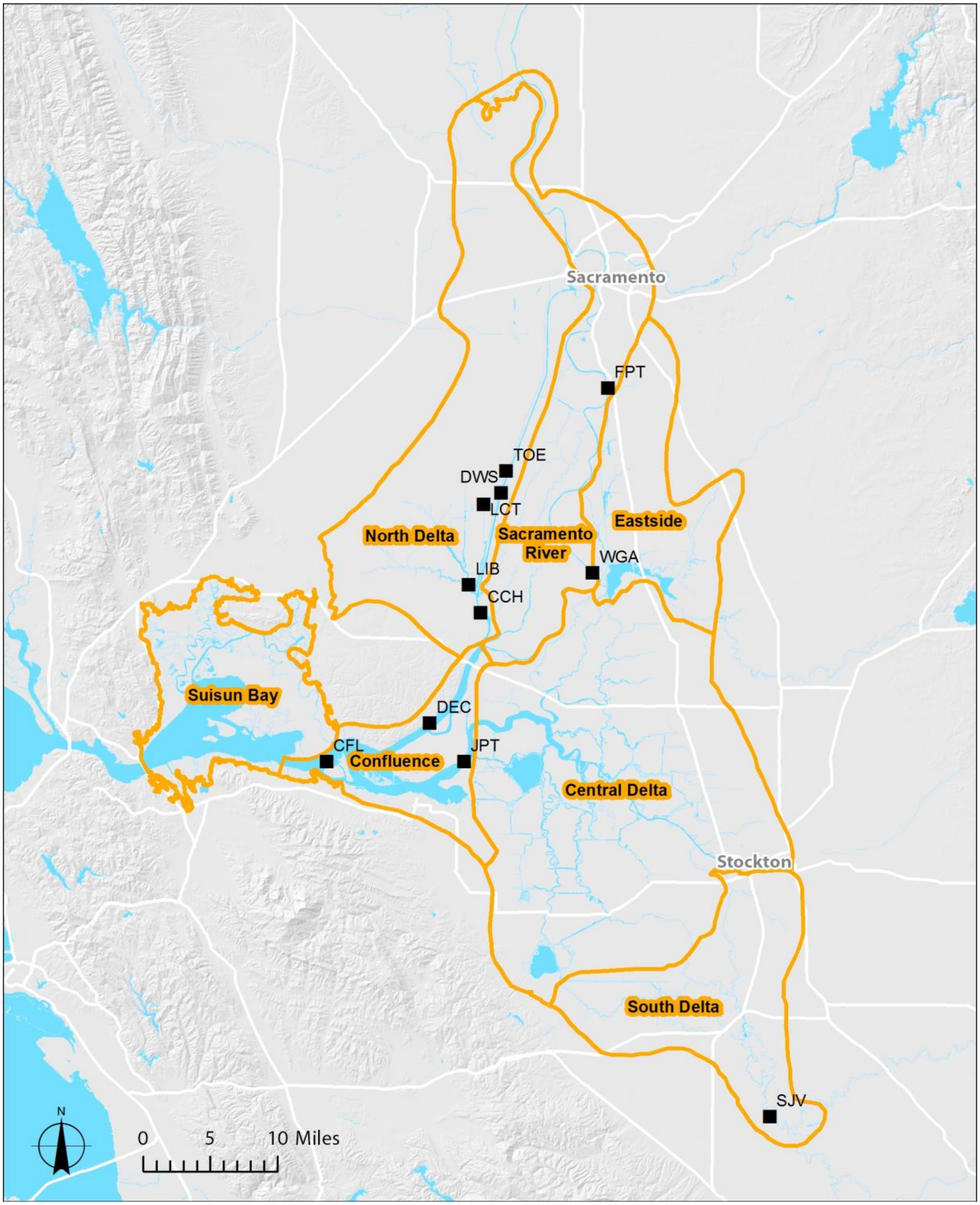

Figure 58. The USGS California Water Science Center currently operates 11 high frequency stations in the Delta: 2 in the Sacramento River subregion, 5 in the North Delta subregion, 3 in the Confluence subregion, and 1 at Vernalis in the South Delta subregion.

The data synthesis prepared for the Delta RMP focused on data for the North Delta stations and Sacramento River stations generated in WYs 2014 and 2015.

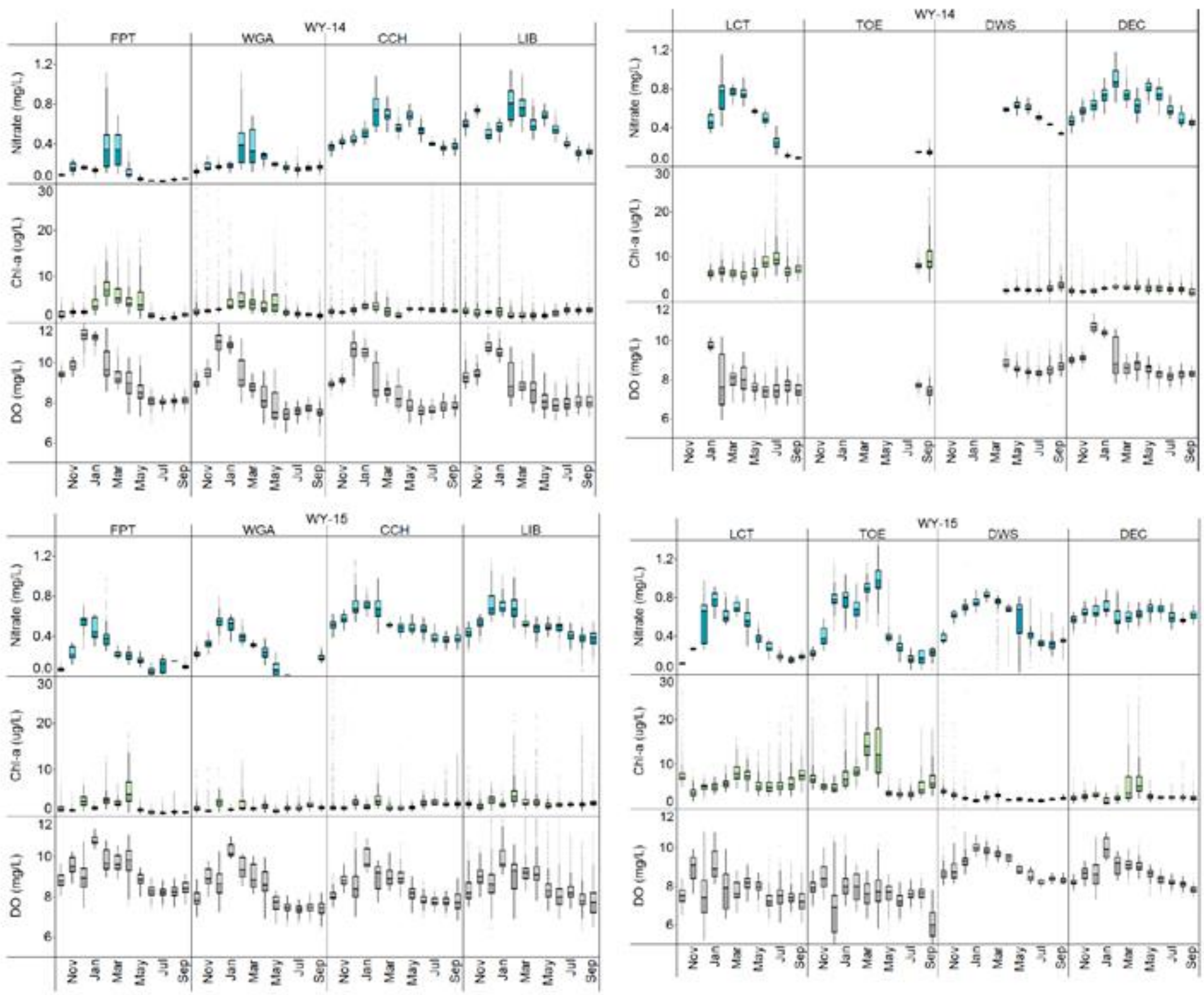

Figure 59. Box and whisker plots of NO_3, chlorophyll-a (Chl-a), and dissolved oxygen (DO) at USGS HF sensor stations in WYs 2014 and 2015.

The boxes show median concentration and 25th/75th percentiles, and the whiskers extend to 1.5x the interquartile range. Dots represent outliers. (Adapted from Downing et al. 2016).

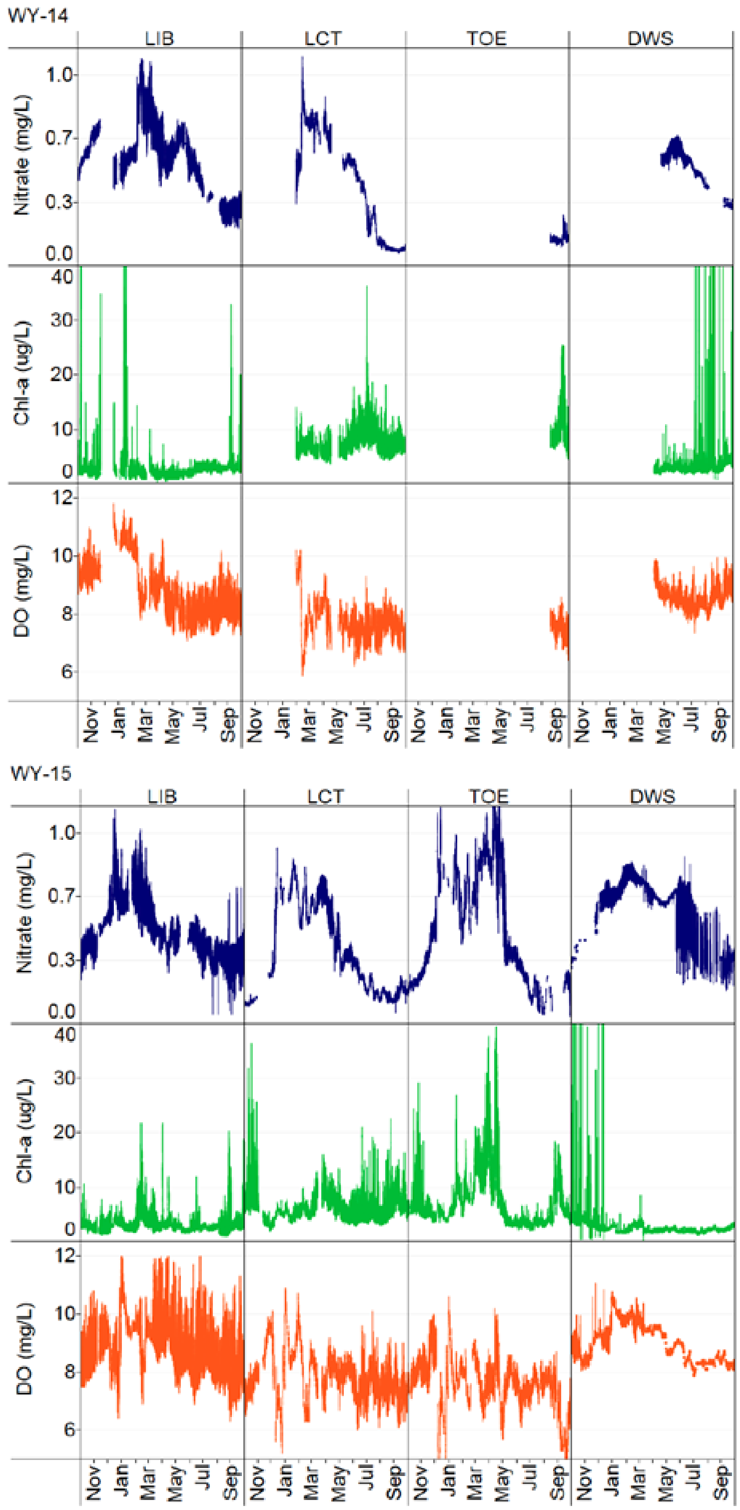

Figure 60. HF measurement time series for nitrate, chlorophyll-a, and dissolved oxygen in WY14 and WY15 at North Delta stations. (Adapted from Downing et al. 2016).

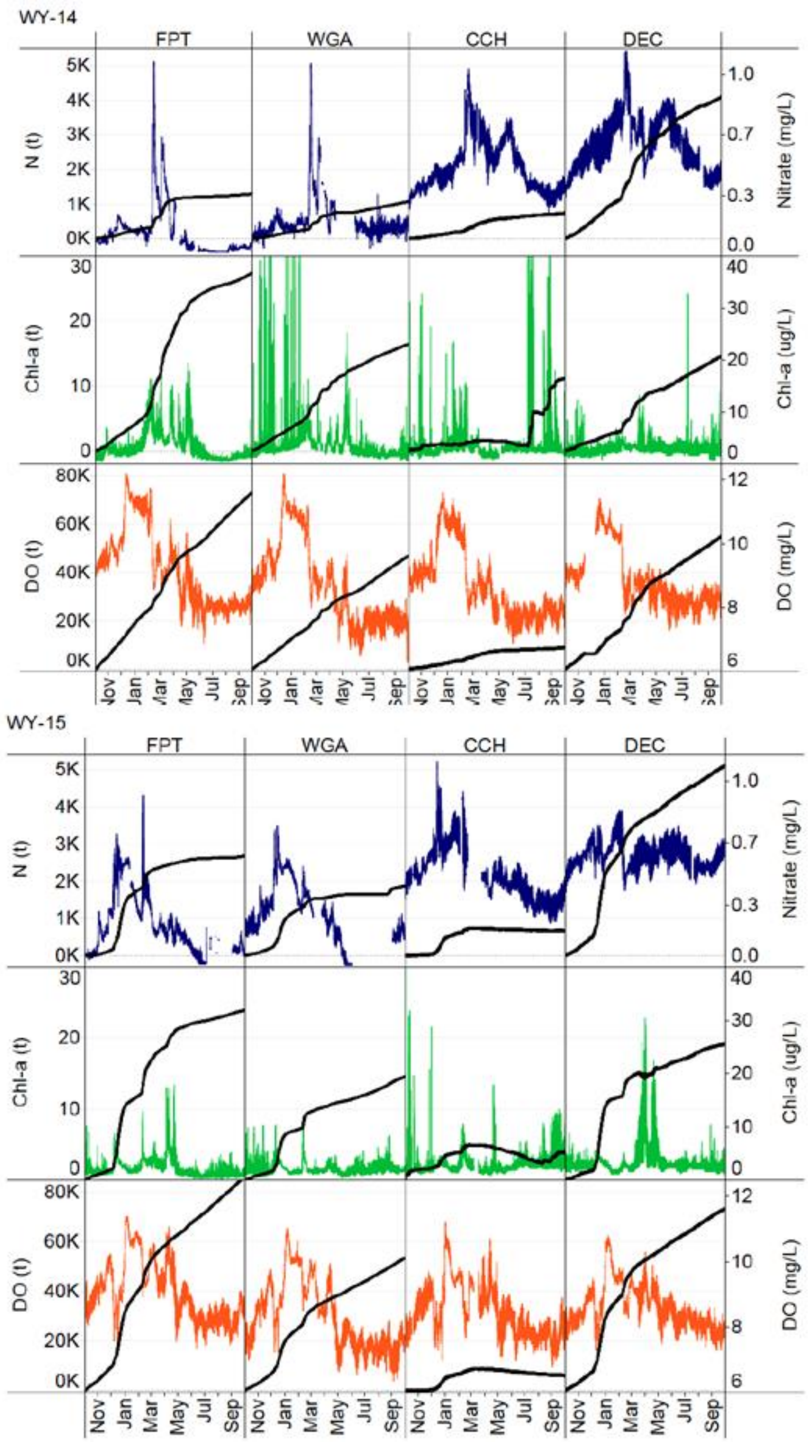

Figure 61. The figures show HF concentration measurement time series and cumulative fluxes for nitrate (blue), chlorophyll-a (green), and dissolved oxygen (orange) in WY14 and WY15 at North Delta stations.

Adapted from Downing et al. (2016). Cumulative fluxes (discharge times concentration) are shown in black.

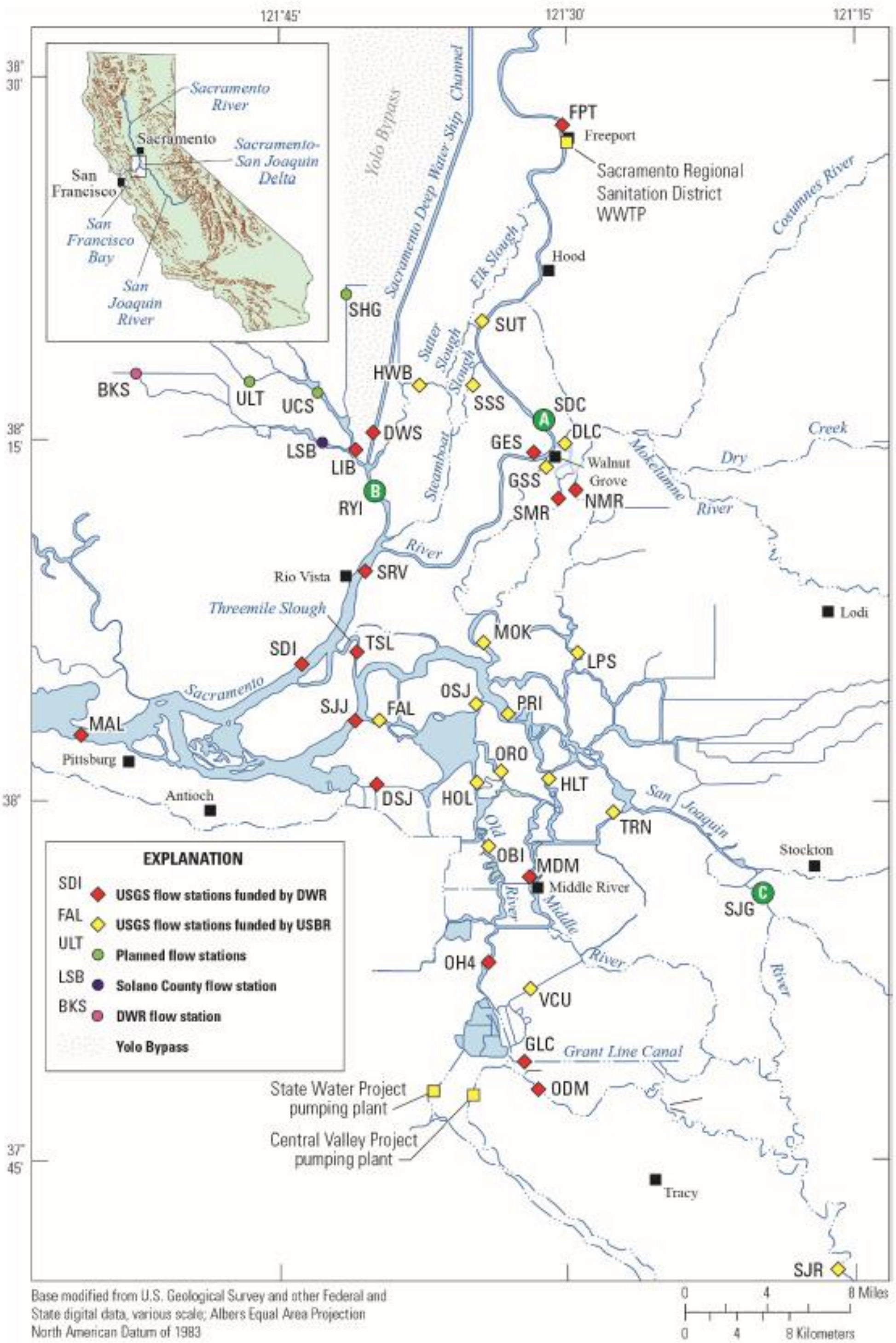

Figure 62. Station locations for HF monitoring network example #1, which includes three stations (see Table 4 for details).

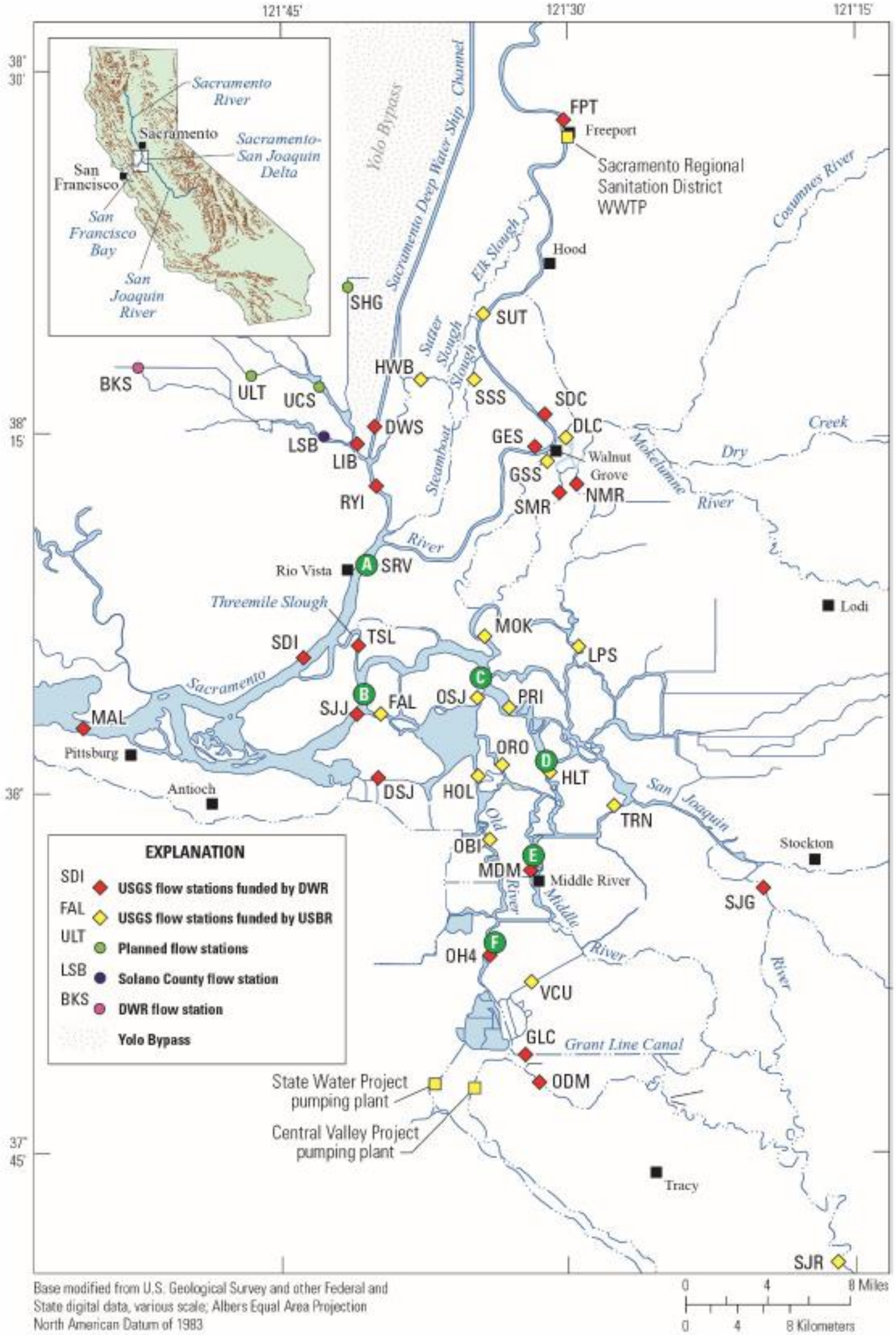

Figure 63. Station locations for HF monitoring network example #2, which includes six stations (see Table 5 for details).

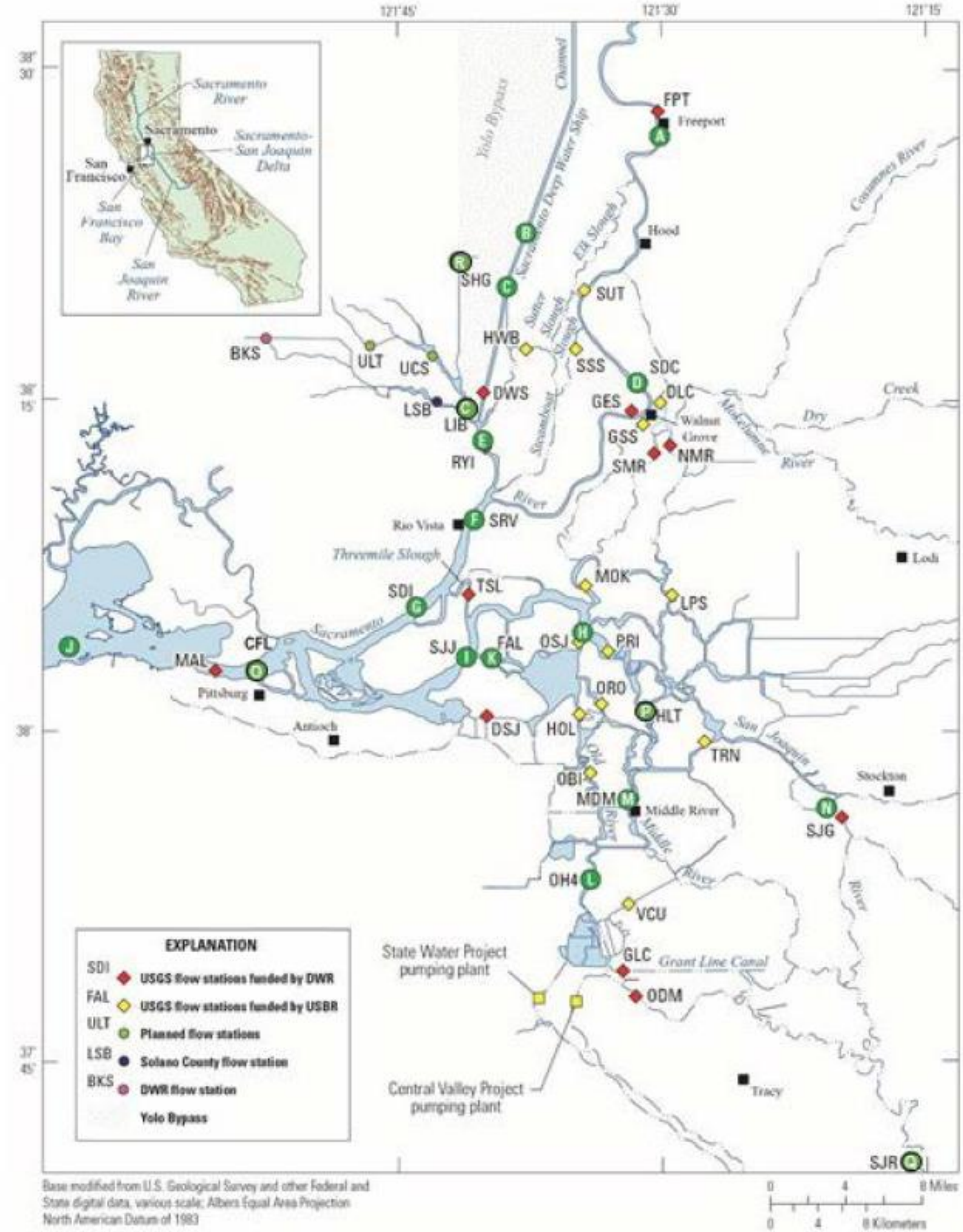

Figure 64. Station locations for HF monitoring network example #2, which includes eighteen stations (see Table 6 for details).

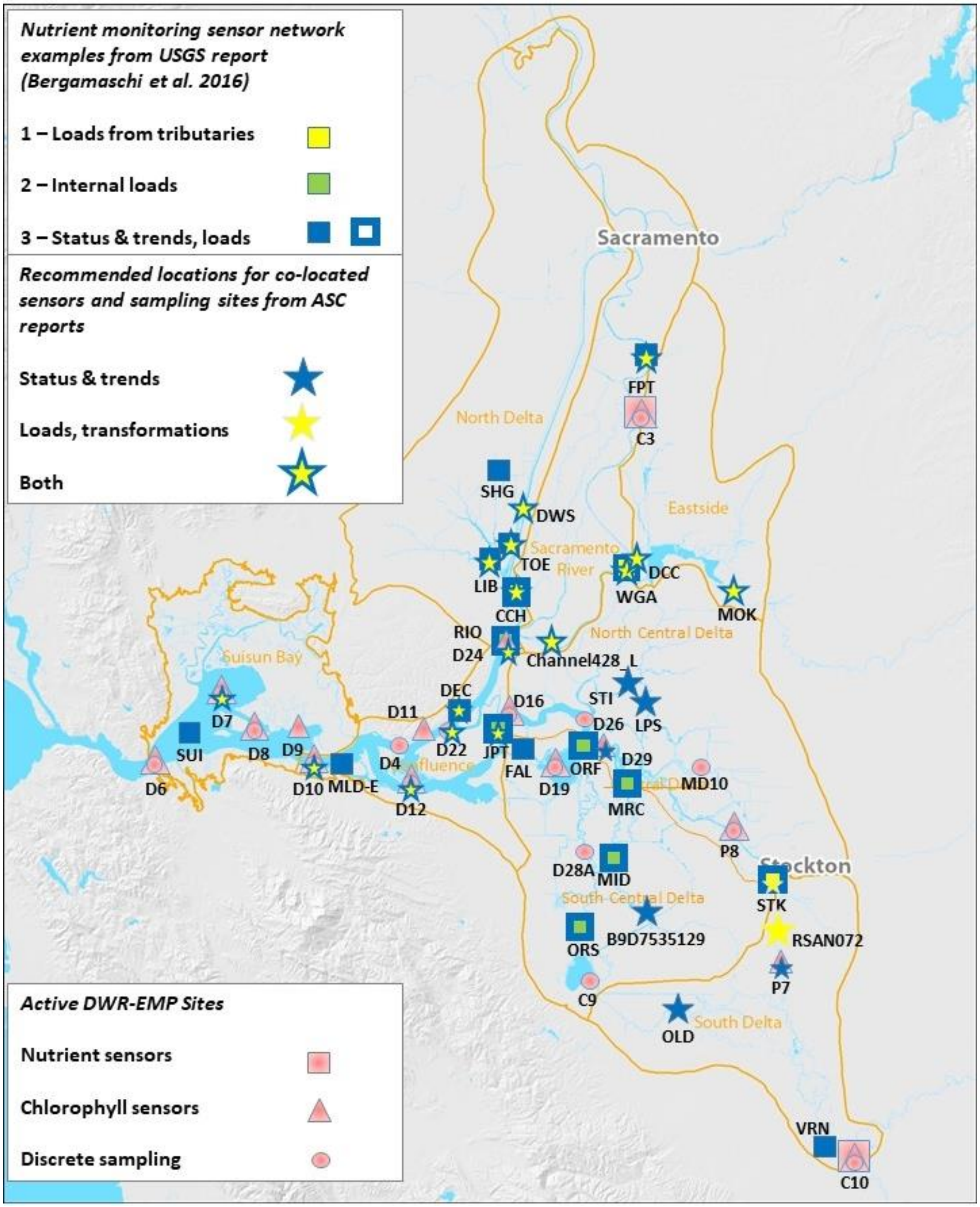

Figure 65. Recommendations for potential monitoring locations for a Delta nutrient monitoring network, provided in synthesis reports developed by USGS and ASC.

The proposed approach is to co-locate high-frequency sensors and discrete sampling site.